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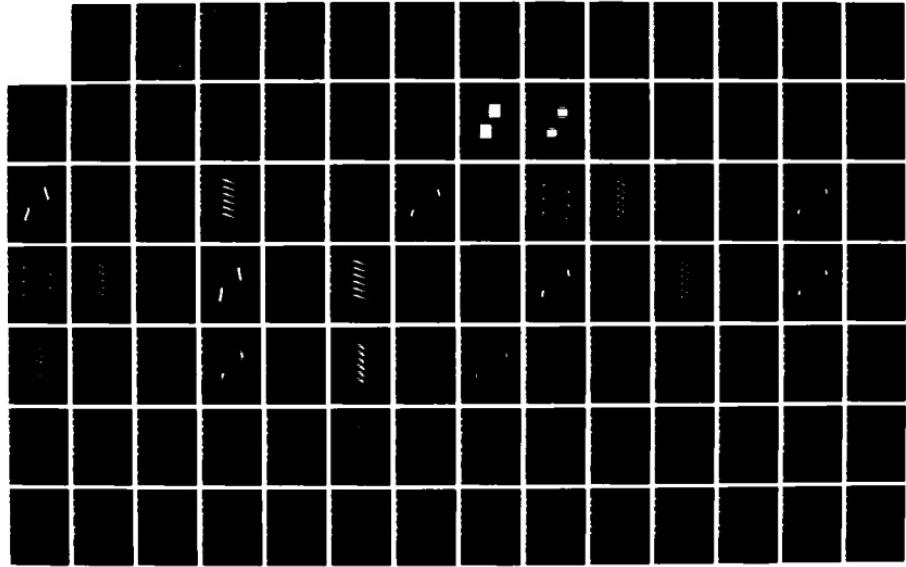
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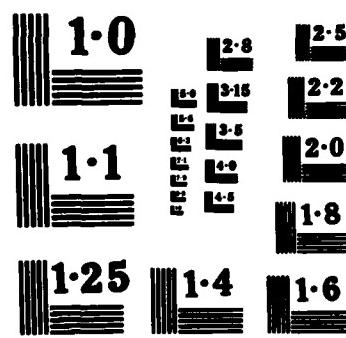
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HARMONIC CONTROL TO REDUCE TORQUE PULSATIONS  
IN BRUSHLESS DC MOTOR DRIVES

Jimmie J. Cathey  
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March 1984

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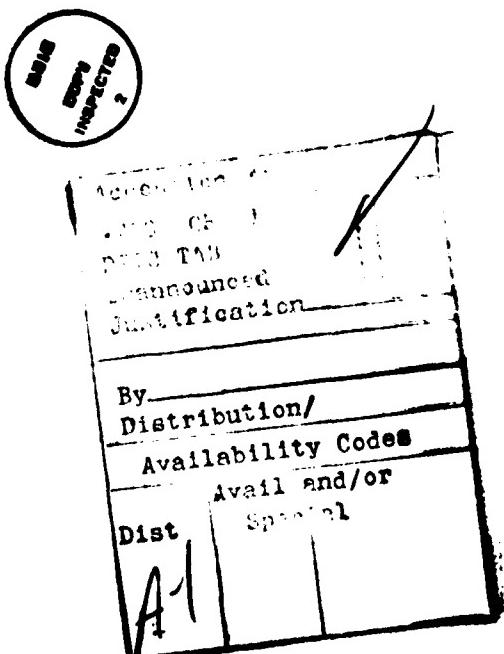
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## SECTION I

### INTRODUCTION

#### 1.0 BACKGROUND

##### 1.1 Orientation

Because of their inherent flexibility of control, reliability, and efficiency, uses of electromechanical actuators and electric drives are finding increased interests in aircraft applications. Three areas of technology advancement over the past decade are largely responsible for placing electromechanical energy converters into a favorable position when compared to hydraulic motors or actuators:

- (a). Development of rare earth permanent magnet (PM) motors with inherent high efficiency and high power to weight ratios.
- (b). Advancements in power level solid-state devices with high switching speeds.
- (c). Emergence of microprocessors allowing control capability and sophistication far surpassing that of analog systems while reducing the volume occupied.

The conventional or commutator DC machine performance characteristics in the areas of speed control and position control are highly desirable. The brushless DC machine has wide range torque-speed characteristics like unto the commutator DC machine without the commutator-brush maintenance problems. In addition, the brushless DC machine with a permanent magnet rotor has certain superior features to the conventional DC machine:

- (a). Field excitation is eliminated, which removes the complexity of supplying power to a rotating member. Also, machine efficiency is increased due to absence of field excitation losses.
- (b). Higher speed design is possible for PM rotors than is feasible with wound rotors permitting increased gear ratios, which leads to substantial reduction in electric machine power to weight ratios.
- (c). Thermal transfer characteristics are improved since the bulk of the losses (ohmic and core losses) are generated within the stationary member, allowing efficient implementation of fluid cooling.

## 1.2 Identification of Problem

Brushless DC motor performance is reported in the literature, but it concentrates on the nature of instantaneous voltage and current along with average values of developed torque [1-9]. These works typically describe systems that do not operate continuously at near zero speed, and thus, only average value of torque is of concern. However, the brushless DC machine inherently has oscillatory components of instantaneous torque at all frequencies that are integer multiples of six times the electrical radian of the stator impressed voltage. Since stator frequency is directly related to rotor position, these oscillatory components are in the frequency range of mechanical system response at low speed values.

Published works relating to performance of brushless DC machines have not analyzed cases of position or sustained near zero speed operation; thus, pulsating torque components have been considered of no significant consequence. However, Williamson et al [10] have mentioned that torque capability deteriorates at low speeds, and Demerdash and Nehl have shown some instantaneous developed torque and power wave forms [11] without comment on the oscillatory components.

Widespread usages of brushless DC motor drive systems in low-speed and position-control actuator applications are contingent upon development of control philosophies and hardware realizations of power conditioning arrangements that allow bidirectional power flow while resulting in instantaneous motor developed torques that are free of harmonics in the range of response for coupled mechanical loads.

## 1.3 Consideration of Alternative Technologies

There are two basic power electronic circuits that are used as power conditioning links to couple brushless dc motor drives to a high frequency, three-phase AC source:

- (a) DC link inverter
- (b) Cycloconverter link

Power circuits of these two basic approaches are illustrated in functional block form by Figure 1. Variations of each arrangement are made according to the control philosophy adopted to satisfy required motor performance. Further, for low voltage (500 V or less), low current (200 A or less) applications, power circuits can be synthesized with transistors for controlled switching elements, while for high power level applications silicon controlled rectifiers (SCRs) must be used for controlled switching elements. For this study, SCR switching elements are assumed.

**1.3.1 Operation for Speeds Not Near Zero.** For the case of a DC link inverter driving a brushless DC motor that does not operate at near zero

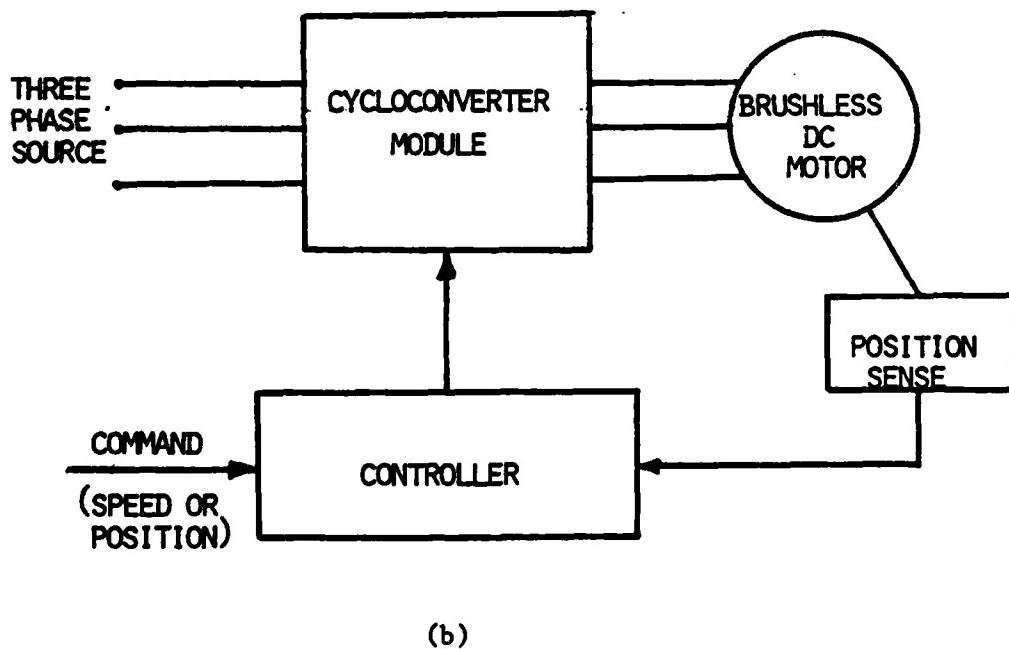
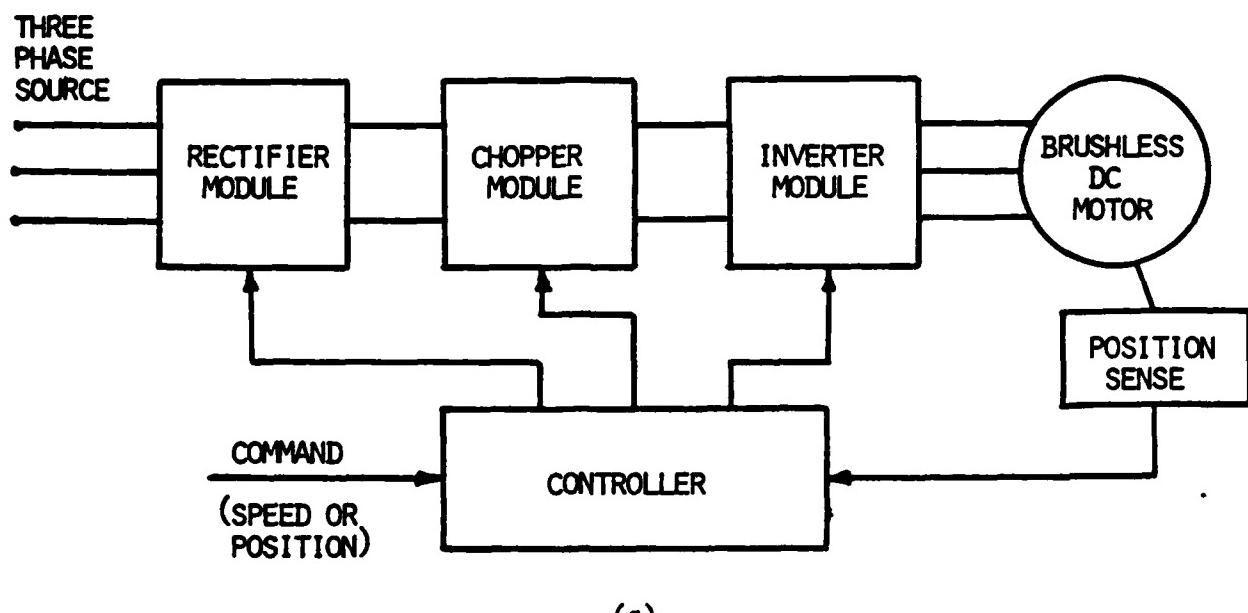


Figure 1. Alternative Power Circuits  
 (a) DC Link Inverter  
 (b) Cycloconverter Link

speed, the rectifier may be a diode bridge while the chopper is used to vary magnitude of DC voltage applied to the inverter input terminals; or, the chopper may be eliminated and a phase-controlled converter used as the rectifier to vary inverter input voltage.

For the case of a cycloconverter, the necessity of a DC link does not exist, and thus, there is only one power conditioning module interconnecting the three-phase AC source with the brushless DC motor. Generally, the cycloconverter may be realized as either a midpoint or a full-bridge arrangement and either phase-control or synchronous envelope operation implemented.

**1.3.2 Operation for Speeds Near Zero.** For near zero speed operation of a DC link inverter for high power level systems, the counter emf of each motor phase is small enough so that natural commutation of the inverter SCRs is prohibited. In such a case, the chopper is used to reduce inverter terminal voltage to zero sufficiently long to accomplish commutation of the inverter SCRs [3]. Since the chopper must be controlled so as to enhance inverter commutation, the rectifier must be a phase-controlled converter to permit necessary inverter input voltage magnitude control.

For near zero speed operation of a phase-controlled cycloconverter using circulating current free mode, discontinuous load current tends to occur, leading to increase in load current harmonics. Continuous current can be restored by changing to circulating current mode of control at the expense of increased losses due to circulating reactive current [12]. Control is generally simplified at fractional hertz frequency operation by use of synchronous envelope control with circulating current free mode.

**1.3.3 Operation for Regenerative Power Flow.** For the case of a DC link inverter, regenerative power flow requires further power circuit modification. Gating signals to inverter SCRs are suppressed and the associated shunting diodes function to form a full-bridge diode rectifier. A switching circuit is introduced in the DC link to reverse polarity of the voltage appearing at the DC terminals of the rectifier module. The rectifier must be a phase-controlled converter operated in the synchronous inversion mode. Reversal of motor developed torque requires three coordinated control actions: phase forward and suppression of inverter SCRs; polarity reversal switch activation; and, phase forward of phase-controlled converter SCRs.

Regenerative power flow using the cycloconverter link is introduced by simply delaying SCR firing angles beyond 90°. Rate of change of motor developed torque from a positive to a negative value is controlled by the rate at which the SCR firing angles are changed. Thus, the nature of transition from motoring to regeneration is determined by a single control action leading to smooth change with minimum time delay.

## 2.0 OBJECTIVE

Of the presently available power conditioning technologies for linking the brushless DC motor to a high frequency polyphase AC source in a near zero speed or actuator application, the cycloconverter using synchronous envelope control with circulating free current mode of operation appears most promising in that it requires no external commutation circuitry and it can be smoothly and quickly changed from motoring to regeneration by a single control action. This arrangement using a mid-point, three-pulse cycloconverter is chosen for study with pulse width modulation (PWM) control to eliminate those harmonics from the output waveform that lead to harmonics in the developed torque in the range to which coupled mechanical loads can respond.

## 3.0 SCOPE

The following tasks were carried out to accomplish the objective:

- (a). Determine an appropriate mathematical model of the system for near zero speed operation.
- (b). Determine the current harmonics to be eliminated in order to remove undesirable pulsations in motor developed torque.
- (c). Develop a modulation function to use in control of phase voltage for eliminating the undesired current harmonics.
- (d). Calculate motor performance over a wide speed range with and without the PWM phase voltage.
- (e). Compare ohmic losses with and without PWM to assess the effect of harmonic elimination on efficiency.

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## SECTION II

### PROCEDURE

#### 1.0 SYSTEM DESCRIPTION

Typical values for motor parameters were obtained by ratio of known values reported in the literature [11] where the results are given in Table 1. The motor is wye connected with a maximum design speed of 45000 rpm.

TABLE 1. MOTOR PARAMETERS

Parameter	Symbol	Value
No. poles	p	4
EMF constant	K	0.0225 V·s/rad
Stator resistance	R <sub>a</sub>	0.4 Ω
Stator leakage inductance	L <sub>a</sub>	25 μH

Characteristics of the balanced three-phase source are listed in Table 2.

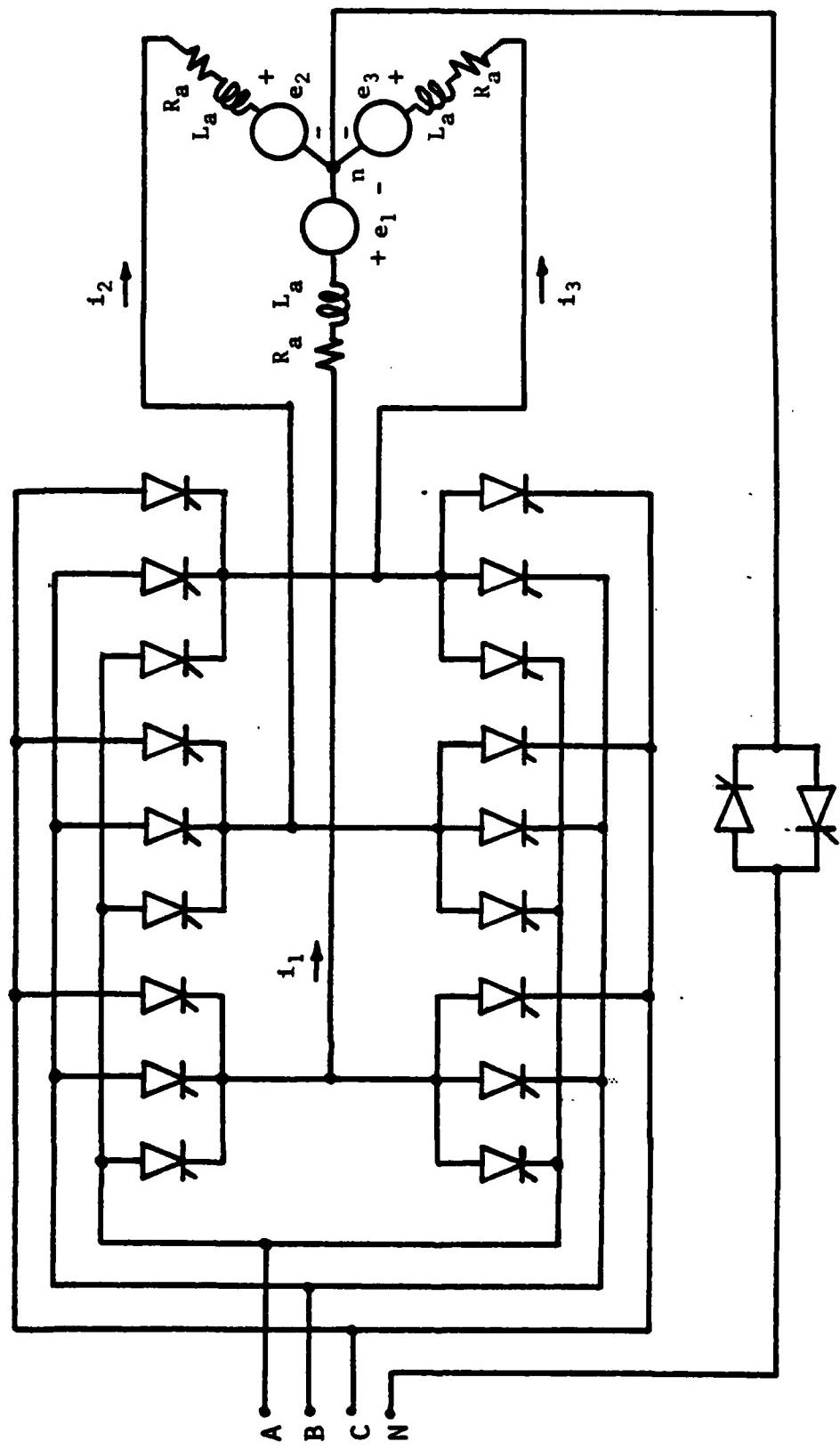
TABLE 2. SOURCE CHARACTERISTICS

Quantity	Value
Phases	3
Line voltage	138 V
Frequency	7950 Hz

The power circuit schematic of a midpoint, three-pulse cycloconverter linking the high frequency, three-phase AC source to the brushless DC motor is depicted by Figure 2. Use of the switch in the midpoint or neutral line will be discussed later.

#### 2.0 ASSUMPTIONS

When analyzing rare earth permanent magnet machines with non-magnetic retaining rings, it has been found that position dependence and interphase



TORQUE HARMONIC ELIMINATOR SWITCH

Figure 2. Schematic of Power Circuit

coupling of machine inductances can be neglected [11]. Such an approximation leads to decoupled equations that can be used in networks formed by addition of power conditioning circuitry with minimum difficulty. Motor counter emfs are taken to be sinusoidal. Further, since the study of this report is concerned with low speed operation, the commutation overlap is very small compared with a period of the motor current wave form and can be neglected.

The SCRs are modelled by a 0.02 ohm forward resistance (2 V at 100 A) and a blocking resistance described by  $1000 i^2$  ohms.

### 3.0 MATHEMATICAL MODEL

Referring to Figure 2, using the above assumptions, and applying Kirchhoff's voltage law results in the following set of simultaneous differential equations to describe the motor electrical performance:

$$\frac{di_1}{dt} = \frac{1}{L_a} (-i_1 R + v_{an} - e_1) \quad (1)$$

$$\frac{di_2}{dt} = \frac{1}{L_a} (-i_2 R + v_{bn} - e_2) \quad (2)$$

$$\frac{di_3}{dt} = \frac{1}{L_a} (-i_3 R + v_{cn} - e_3) \quad (3)$$

$R_1$ ,  $R_2$ , and  $R_3$  are the sum of the motor phase resistance and the resistance of the particular SCR between the source and phase of the motor at the particular instant of time under analysis. The form of phase voltages ( $v_{an}$ ,  $v_{bn}$ ,  $v_{cn}$ ) will be discussed later.

Neutral connection current is given by Kirchhoff's current law as

$$i_{nN} = i_1 + i_2 + i_3 \quad (4)$$

As long as motor speed ( $\omega_m$ ) remains non zero, the electromechanical developed torque is given by

$$T_d = (e_1 i_1 + e_2 i_2 + e_3 i_3) / \omega_m \quad (5)$$

Equations (1) - (5) completely describe the instantaneous performance of the brushless DC motor.

#### 4.0 CURRENT HARMONICS TO BE ELIMINATED

For both the case of a DC link inverter drive and the case of a synchronous envelope cycloconverter drive, the motor phase currents approach the pulse width controlled square wave of Figure 3. A Fourier series representation of the wave form shows that all odd, nontriplet harmonics exist in the phase current.

$$i_1 = \frac{4I}{\pi} \sum_n \frac{1}{n} \cos \left( \frac{n\pi}{6} \right) \sin n\omega t, \quad n = 1, 5, 7, 11, 13, \dots \quad (6)$$

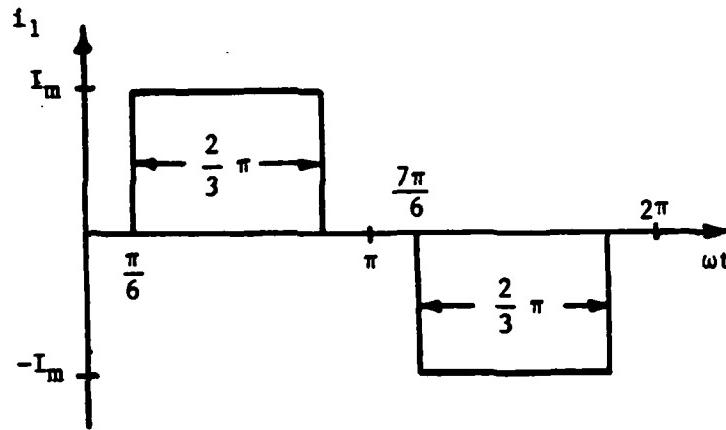


Figure 3. Approximate Form of Motor Phase Current

Similarly, the remaining balanced phase currents are given by

$$i_2 = \frac{4I}{\pi} \sum_n \frac{1}{n} \cos \left( \frac{n\pi}{6} \right) \sin n\left(\omega t - \frac{2\pi}{3}\right) \quad (7)$$

$$i_3 = \frac{4I}{\pi} \sum_n \frac{1}{n} \cos \left( \frac{n\pi}{6} \right) \sin n\left(\omega t + \frac{2\pi}{3}\right) \quad (8)$$

$n = 1, 5, 7, 11, 13, \dots$

Since the motor counter emfs ( $e_1, e_2, e_3$ ) are sinusoids of fundamental frequency and form a balanced three-phase set, each can be expressed as

$$e_1 = E_m \sin(\omega t + \phi) \quad (9)$$

$$e_2 = E_m \sin(\omega t + \phi - \frac{2\pi}{3}) \quad (10)$$

$$e_3 = E_m \sin(\omega t + \phi + \frac{2\pi}{3}) \quad (11)$$

If equations (6) - (11) are substituted into (5), the simplified result for instantaneous developed motor torque is found.

$$T_d = \frac{4}{\pi} E_m I \sum_n \frac{1}{n} \cos\left(\frac{n\pi}{6}\right) \{\cos[(n-1)\frac{\pi}{6}\omega t - \phi] - \cos[(n+1)\frac{\pi}{6}\omega t + \phi]\} \quad (12)$$

$n = 1, 5, 7, 11, 13, \dots$

From (12), it is seen that the instantaneous developed motor torque is made up of a constant term plus all multiples of the sixth harmonic of motor phase current frequency. Further, the multiples of sixth harmonic components of torque are a direct result of the current harmonics that lie immediately on either side of multiples of six. Specifically, the sixth harmonic of torque results from the fifth and seventh harmonic of current; and, the twelfth harmonic of torque results from the eleventh and thirteenth harmonic of current; etc. Clearly, the motor developed torque will be constant if the harmonics of motor phase current described by  $6n \pm 1$ ,  $n = 1, 2, 3, \dots$  are eliminated.

The above discussed harmonics only need to be eliminated if their existence results in torque harmonics in the range of response of a coupled mechanical load. Since typical mechanical loads exhibit negligible response to frequencies above 20 hertz, it should only be necessary to eliminate those nontriplet, odd current harmonics beyond the first for which

$$M < \frac{80\pi}{6p\omega_m} \quad (13)$$

where  $p$  = number of poles and  $\omega_m$  is the motor speed in rad/s.

## 5.0 MODULATION OF PHASE VOLTAGE

The cycloconverter system is voltage excited; thus, if the  $(n \pm 1)$  harmonics are to be eliminated from motor phase currents, they must be eliminated from the phase voltage set.

### 5.1 Development of Modulation Function

Modulation function  $h(\omega t)$  that contains no selected harmonics up through  $M$  is derived in Appendix B. The balanced three-phase voltage set

to be applied for equations (1) - (3) is given by

$$v_{an} = v_d h(\omega t) \quad (14)$$

$$v_{bn} = v_d h(\omega t - \frac{2\pi}{3}) \quad (15)$$

$$v_{cn} = v_d h(\omega t + \frac{2\pi}{3}) \quad (16)$$

If  $\omega_L$  is the radian frequency of the three-phase AC source, then  $v_d$  is a periodic wave form described by

$$v_d(t) = V_m \sin(\omega_L t + \frac{\pi}{6} + \alpha_s), \quad 0 \leq \omega_L t \leq \frac{2\pi}{3} \quad (17)$$

$$\text{and, } v_d(t + T) = v_d(t) \quad (18)$$

$$\text{where } T = \frac{2\pi}{3\omega_L}$$

It is shown in Appendix A that if the modulated phase voltages ( $v_{an}, v_{bn}, v_{cn}$ ) are to contain none of the selected harmonics through M, it is necessary that the frequency of  $v_d$  be much greater than the frequency of  $h(t)$ ; however, this condition is easily satisfied at near zero speed.

Figure 4 illustrates the unmodulated phase voltage. The modulated phase voltage is shown by Figure 5.

## 5.2 Minimization of Slack Variable

Development of the modulation function for use with the synchronous envelope cycloconverter in Appendix A required an extension of the well-known pulse width modulation techniques for elimination of harmonics in inverter drives [14] to include a slack variable. The modulation function contained no selected harmonics through M as determined by (13). For the reported work, the slack variable is always chosen so as to minimize the sum of the squares of the amplitude of the next higher ( $6n \pm 1$ ) current harmonic pair beyond harmonics selectively eliminated. Listings of the FORTRAN programs used to compute the modulation function are presented in Appendix B.

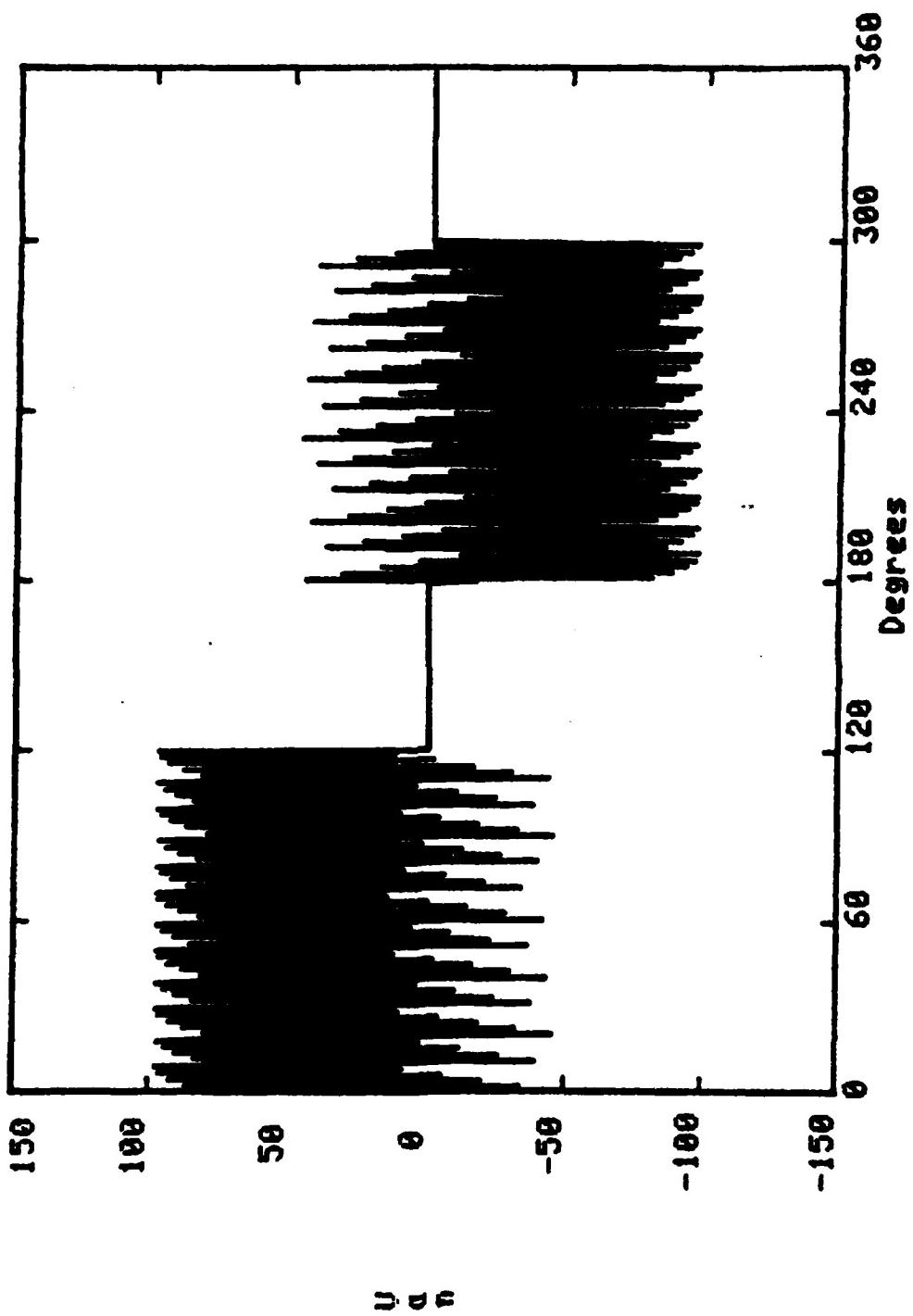
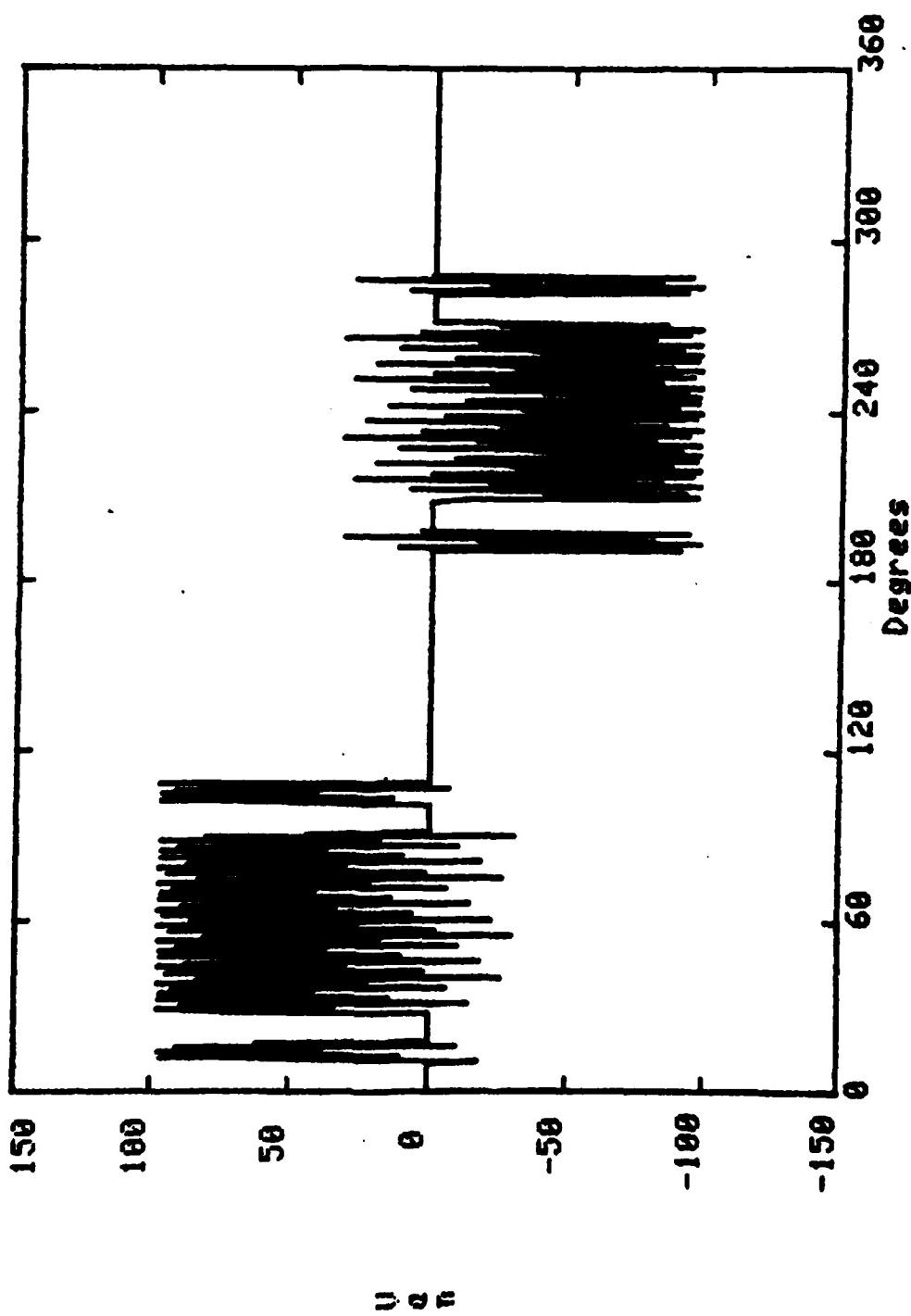


Figure 4. Unmodulated Phase Voltage

Figure 5. Modulated Phase Voltage



### 5.3 Cycloconverter Connection Method

Since the modulation function  $h(\omega t)$  does not repeat itself every  $\pi/6$  radians on the interval  $[\pi/6, 5\pi/6]$ , attention must be directed to the cycloconverter connection scheme utilized so that the eliminated harmonics are not inadvertently reintroduced. Specifically, a conduction path must be provided so that all harmonics remaining in the phase voltage can flow if the phase current is to be of the same harmonic content. Two connection realizations are possible wherein no restriction on phase current harmonics are imposed by Kirchhoff's current law. The first of these acceptable connections is that of the midpoint cycloconverter with the neutral lead in place. A second realization would be the full-bridge cycloconverter with total phase isolation. Since this latter connection requires 36 SCRs, it was not used in the reported study due to a factor of three on component requirement over the midpoint cycloconverter case. However, it should be pointed out that the full-bridge cycloconverter with its six-pulse output has a smaller ripple magnitude and may offer a slight efficiency advantage.

### 5.4 Fourier Spectrum Analysis

Nature of the waveforms for current and instantaneous developed torque are such that visual inspection to determine harmonic content is not practical or accurate. The listing of a FORTRAN program to find the Fourier coefficients is given in Appendix D.

This program was used to generate the data for the normalized Fourier spectrum plots of Section III for harmonics up through forty-eight in order to verify that attempt to selectively eliminate harmonics was successful.

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### SECTION III

#### RESULTS

##### 1.0 SUMMARY

Three speed conditions were selected for numerical study to evaluate the effectiveness of the harmonic elimination technique in removing undesired torque pulsations from the midpoint cycloconverter driven brushless DC motor system when using synchronous envelope control:

- (a). 4500 rpm (10% speed case)
- (b). 2250 rpm (5% speed case)
- (c). 450 rpm (1% speed case)

Although these speeds are great enough that elimination of harmonics as determined by equation (13) would not be necessary, there are two reasons for their selection. The first is conservation of computer time. Computation of a set of data for the 450 rpm (1% speed case) required approximately 8 hours of CPU time on a Control Data PDP 11/44 computer. Since many trial-and-error runs were necessary for each data set, runs at lower motor speed become prohibitive timewise. Secondly, if the harmonics can be successfully eliminated at higher speeds, then there is not difficulty to be encountered at reduced speed. Justification lies in the fact that the undesired harmonics are totally eliminated from the phase voltage set. Any re-introduction of the undesired harmonics into the phase current wave forms would be attributable to commutation overlap which is dependent on the  $L_a/R$  time constant that determines current decay at the end of each phase current conduction sequence. Since this time constant is not speed dependent, the commutation overlap interval is a larger portion of the current wave form period at high speed than it is at low speed. Thus, the departure of phase current from the form of the phase voltage is greater at high speed than at low speed. It is concluded that if undesirable harmonics are not re-introduced at high speed, then success at low speed is guaranteed.

For each speed case, the nature of current and torque were examined for application of a balanced set of phase voltages of the following nature:

- (a). No harmonic eliminated.
- (b). Fifth and seventh harmonics eliminated.
- (c). Fifth, seventh, eleventh, and thirteenth harmonics eliminated.

A brushless DC machine system has an extra input or degree of freedom over either a conventional DC machine or a synchronous machine drive system in that the angular displacement between the stator and rotor magnetic fields can be specifically controlled. For this study, this extra degree of control freedom is implemented by specification of the angle ( $\alpha$ ) measured from the onset of positive phase current conduction to the positive going zero crossing of the associated motor phase counter emf. A convenient value ( $\alpha = 30^\circ$ ) is used for most of the study; however, since selection of  $\alpha$  shifts the position of motor phase counter emf with respect to phase current, the nature of commutation overlap can be altered by the value of  $\alpha$ . The effect of changing  $\alpha$  over the range from  $15^\circ$  to  $40^\circ$  is studied for one speed case.

## 2.0 PERFORMANCE STUDIES

Equations (1) - (3) can be written in compact matrix form as

$$\frac{d}{dt} \underline{i} = \frac{1}{L_a} [R] \underline{i} + \frac{1}{L_a} \underline{v}_\phi - \frac{1}{L_a} \underline{e} \quad (20)$$

where:

$$\underline{i} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \quad (21) ; \quad \underline{e} = \frac{2\omega K}{p} \begin{bmatrix} \sin(\omega t - \alpha) \\ \sin(\omega t - \alpha - \frac{2\pi}{3}) \\ \sin(\omega t - \alpha + \frac{2\pi}{3}) \end{bmatrix} \quad (22)$$

$$[R] = \begin{bmatrix} R_1 & & \\ & R_2 & \\ & & R_3 \end{bmatrix} \quad (23) ; \quad \underline{v}_\phi = v_d(t) \begin{bmatrix} h(\omega t) \\ h(\omega t - \frac{2\pi}{3}) \\ h(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (24)$$

Equation (20) is a nonlinear set of differential equations due to the elements of  $[R]$  being functions of current. Any attempt at linearization for a wide range of  $\underline{i}$  would unacceptably alter the physical nature of the problem by removing the rectifying characteristic of the SCRs. Consequently, a closed form solution of (20) is not possible and a numerical integration must be implemented. A fixed increment ( $1.0 \times 10^{-6}$ s) fourth-order Runge-Kutta numerical integration method is utilized for this work.

After forming a modulation function through use of the programs of Appendix B, selecting a particular motor speed ( $\omega_m = 2\omega/p$ ), and arbitrarily choosing a value of SCR firing angle  $\alpha_s$  (see equation (17)), numerical solution to (20) is implemented subject to initial conditions  $\underline{i}(0) = \underline{0}$ . Integration is continued until steady-state is reached. Instantaneous values of developed torque are calculated according to (5) and numerically

averaged over the last steady-state cycle of integration to give the average value of developed torque. This value of average torque is compared with a specified value for the operating point. If the average value calculated is different from the specified value, then  $\alpha_s$  is appropriately adjusted and the numerical integration is repeated until the difference magnitude between calculated and specified torque are sufficiently close in an epsilon sense. For all cases studied, the specified torque was taken as 1.5 N·m.

The listing of a FORTRAN program to compute the performance as described above is presented in Appendix D. In addition to the discussed computations, the program also calculates the RMS value of phase current over the last steady-state cycle as  $(\frac{1}{T} \sum i^2 \Delta t)^{\frac{1}{2}}$ . Also, values of phase current and instantaneous torque are stored over the last steady-state cycle for use by the Fourier Spectrum Program of Appendix C.

Results of the various speed cases and harmonic elimination studies are summarized in the paragraphs that follow.

## 2.1 4500 RPM (10% Speed Case)

### 2.1.1 Unmodulated Phase Voltage.

#### Input Data

Motor speed,  $n_m$  = 4500 rpm  
Motor frequency,  $f$  = 150 Hz  
SCR firing angle,  $\alpha_s$  = 58.68°  
Specified average torque,  $T_{dav}$  = 1.5 N·m

#### Output Data

Average torque,  $T_{dav}$  = 1.501 N·m  
RMS phase current,  $I_{RMS}$  = 72.77 A

A plot of phase current  $i_1$  is given by Figure 6. The associated Fourier spectrum of  $i_1$  is shown by Figure 7. Predominantly triplen harmonic current that flows through the neutral connection is depicted by Figure 8.

A plot of the instantaneous developed torque where the sixth harmonic is obvious is given by Figure 9. A Fourier spectrum of the instantaneous torque is shown in Figure 10 where existence of all multiples of six as theoretically predicted are noted.

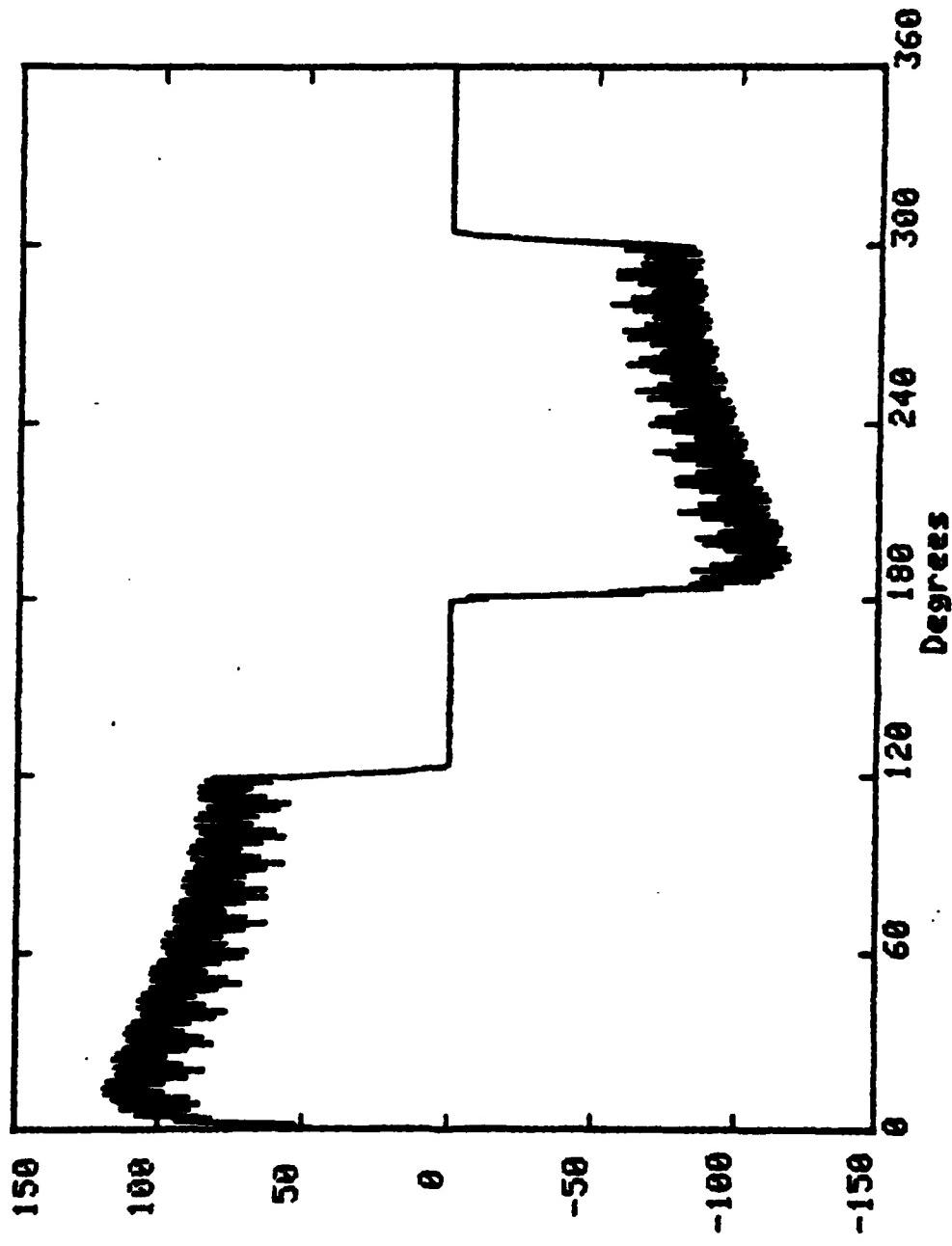


Figure 6. Phase Current - 4500 RPM, No Modulation

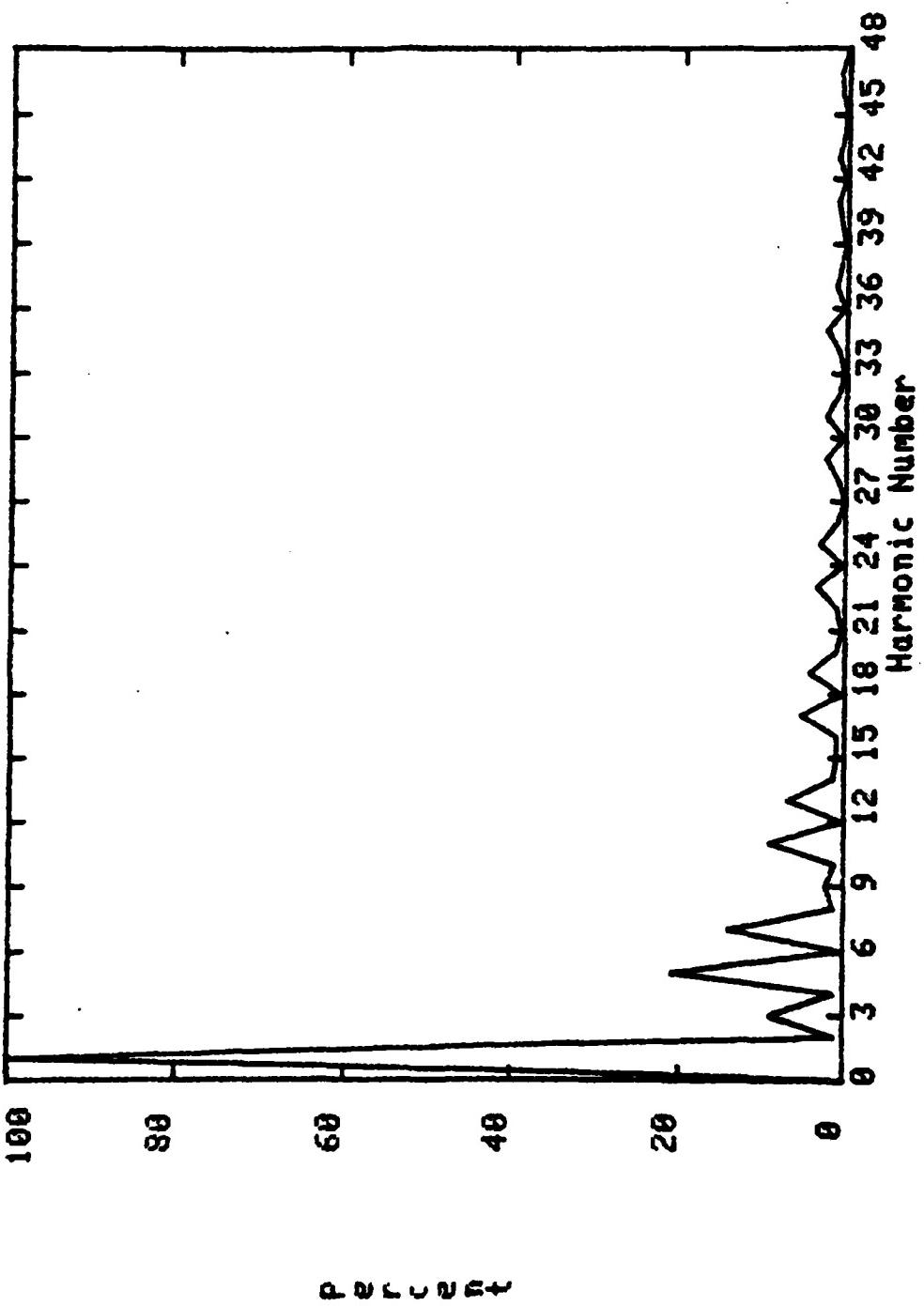


Figure 7. Fourier Spectrum of Phase Current - 4500 RPM, No Modulation

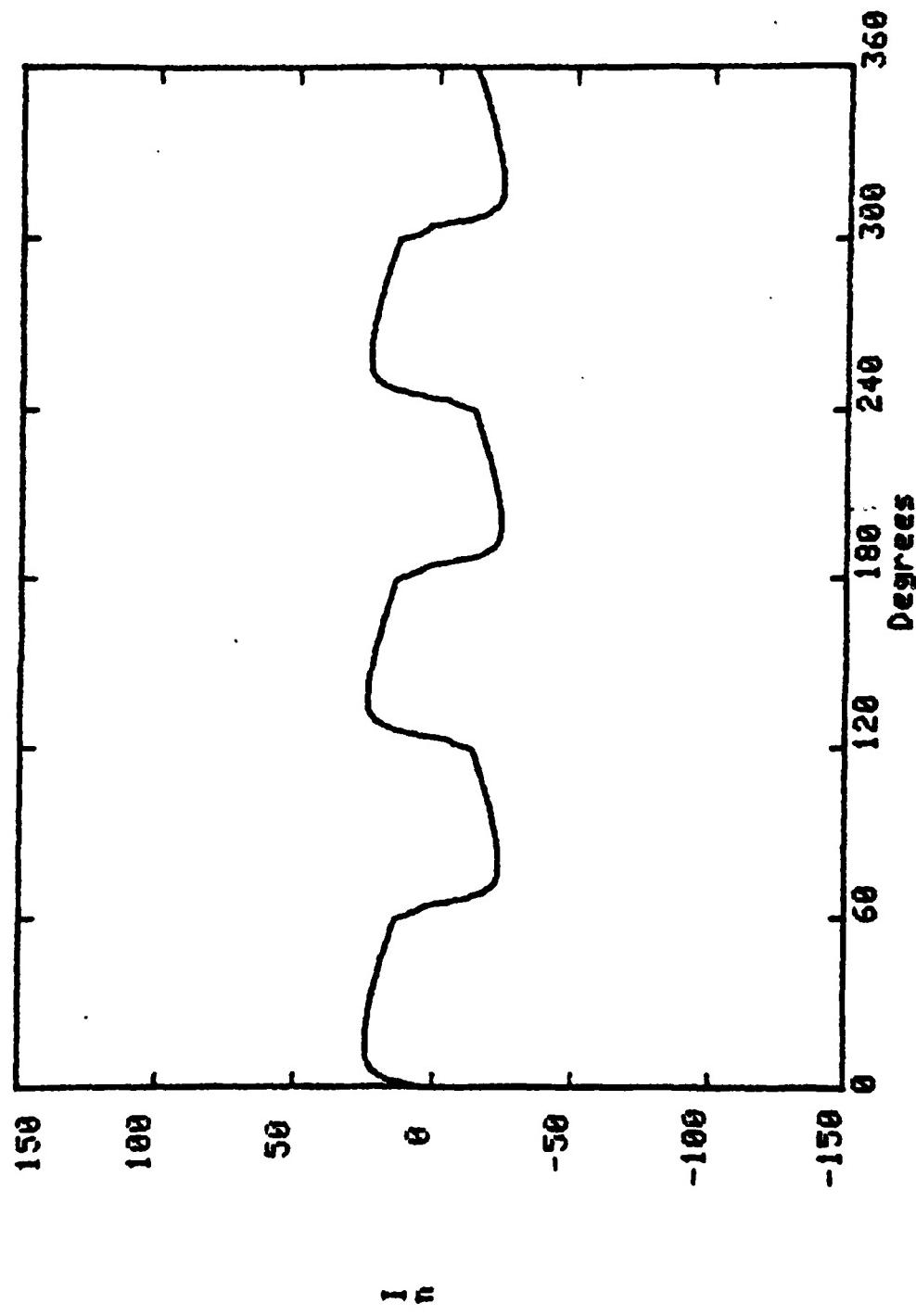


Figure 8. Neutral Current - 4500 RPM, No Modulation

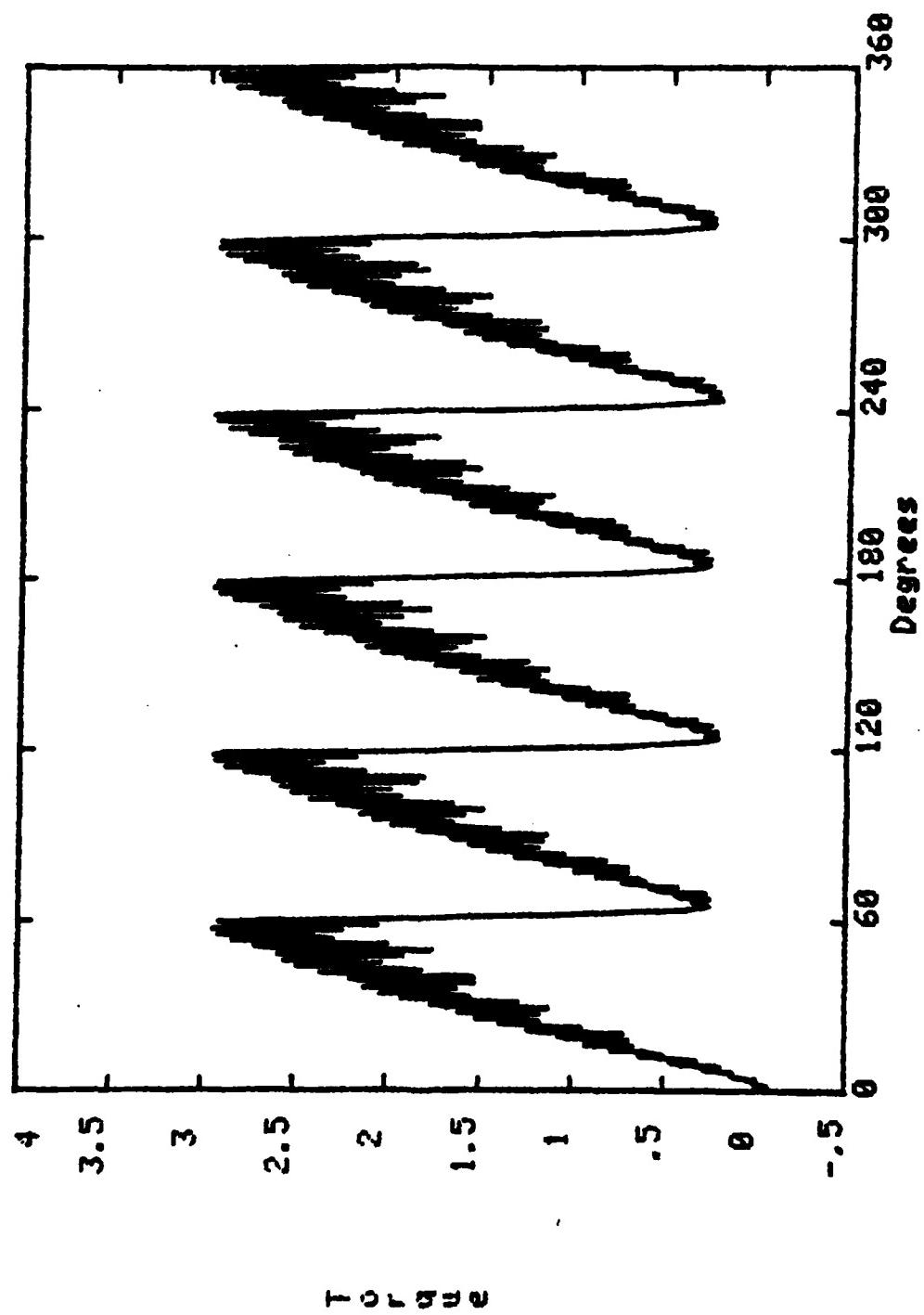


Figure 9. Developed Torque - 4500 RPM, No Modulation

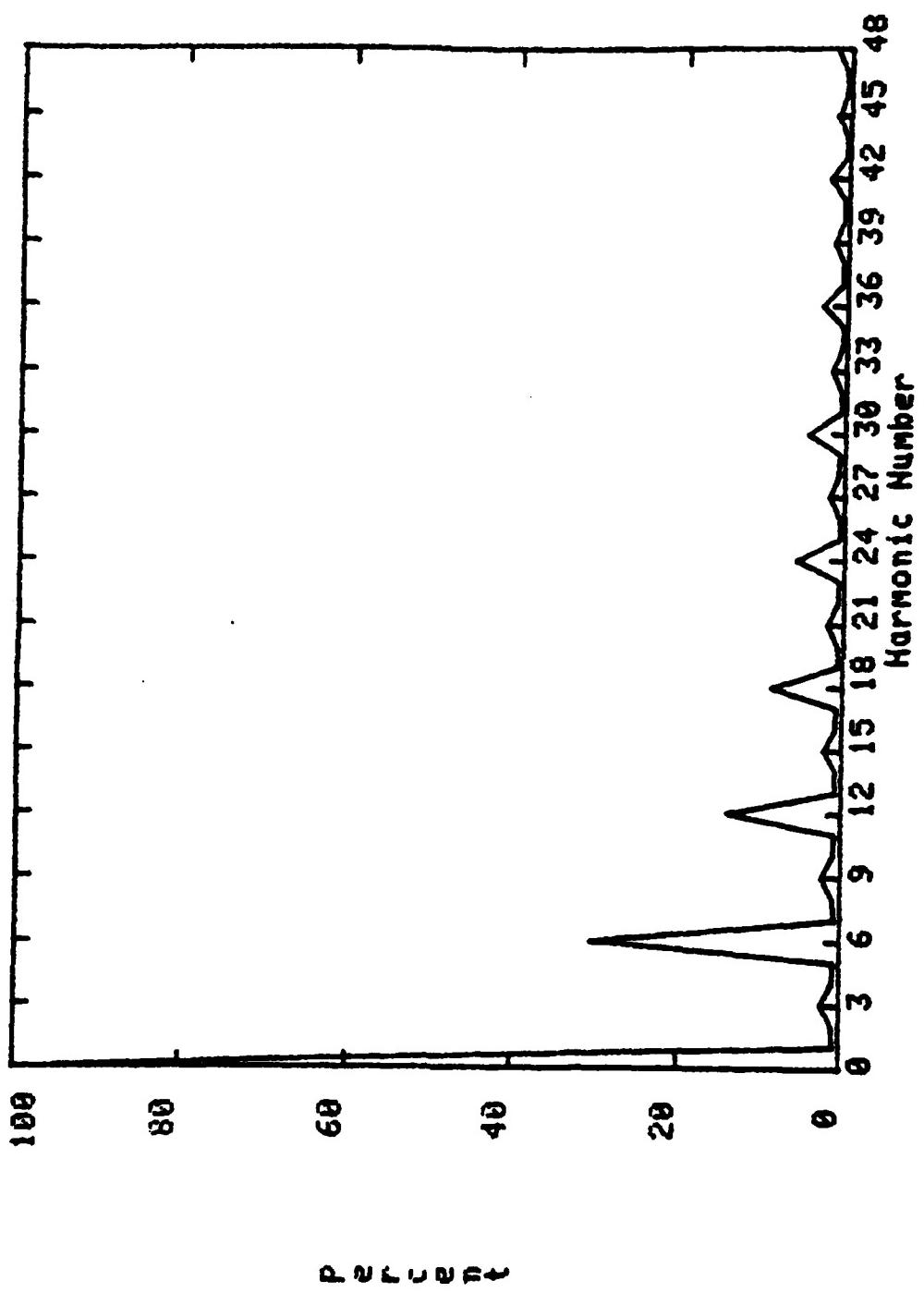


Figure 10. Fourier Spectrum of Developed Torque - 4500 RPM, No Modulation

**2.1.2 Elimination of Sixth Harmonic of Torque.** The sixth harmonic of torque is eliminated by removing the fifth and seventh harmonics of phase current.

Input Data

Motor speed,  $n_m$  = 4500 rpm  
Motor frequency,  $f$  = 150 Hz  
SCR firing angle,  $\alpha_s$  = 46.45°  
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  = 40.76°  
 $\alpha_2$  = 47.73°  
 $\alpha_3$  = 58.65°

Output Data

Average torque,  $T_{dav}$  = 1.5001 N·m  
RMS phase current,  $I_{RMS}$  = 74.24 A

A plot of phase current  $i_1$  is given by Figure 11. The associated Fourier spectrum of  $i_1$  is shown by Figure 12, where negligibly small fifth and seventh harmonics are noted. Current flow through the neutral line is depicted by Figure 13.

A plot of the instantaneous developed torque is given by Figure 14. The Fourier spectrum of the developed torque is shown in Figure 15 where it is seen that the sixth harmonic is near zero.

**2.1.3 Elimination of Sixth and Twelfth Harmonics of Torque.** Both the sixth and twelfth harmonics of torque are eliminated by removing the fifth, seventh, eleventh, and thirteenth harmonics of phase current.

Input Data

Motor speed,  $n_m$  = 4500 rpm  
Motor frequency,  $f$  = 150 Hz  
SCR firing angle,  $\alpha_s$  = 42.63°  
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  = 38.73°  
 $\alpha_2$  = 42.13°  
 $\alpha_3$  = 57.25°  
 $\alpha_4$  = 61.93°  
 $\alpha_5$  = 66.86°

Output Data

Average torque,  $T_{dav}$  = 1.505 N·m  
RMS phase current,  $I_{RMS}$  = 74.59 A

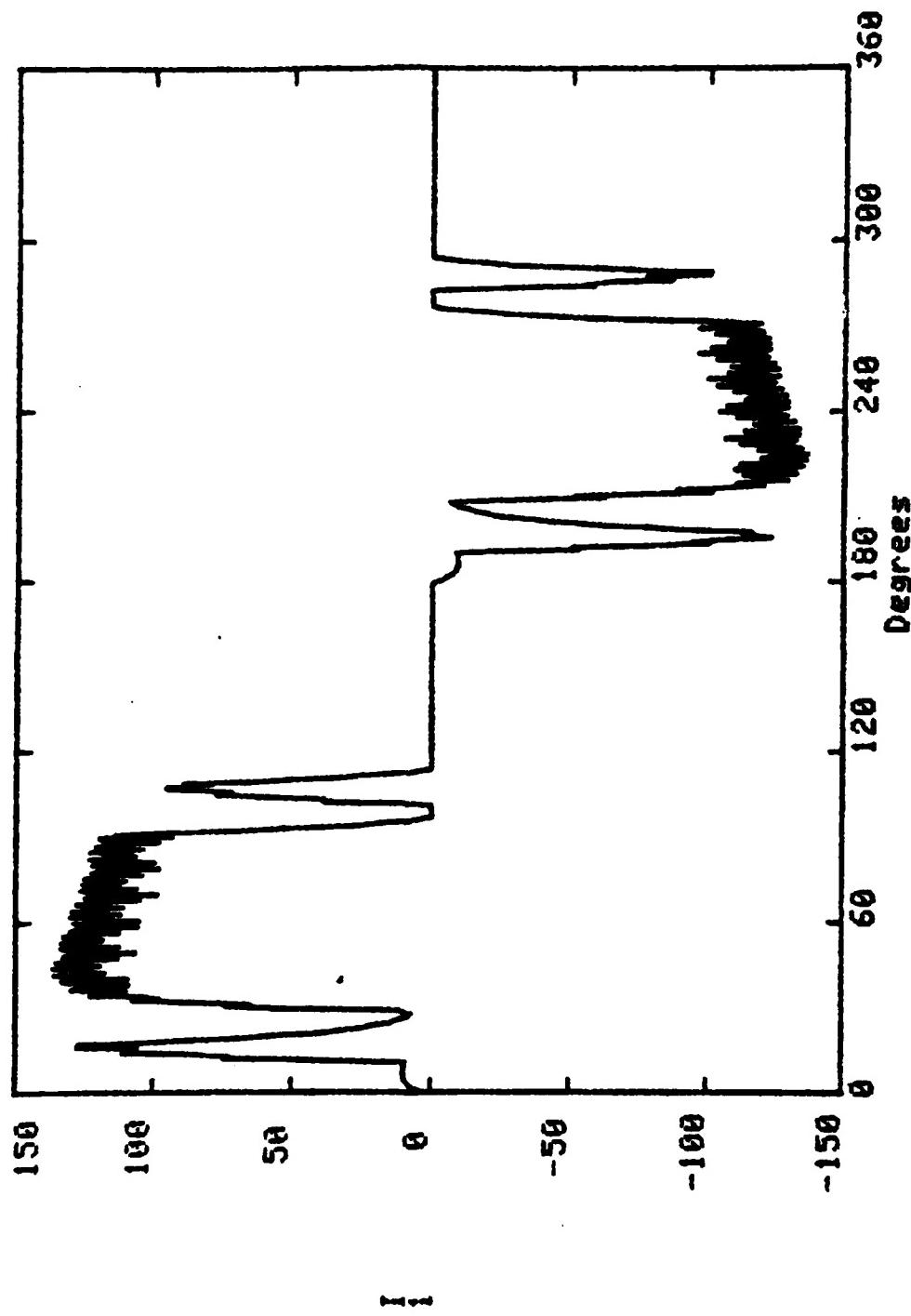


Figure 11. Phase Current - 4500 RPM, Fifth and Seventh Harmonic Eliminated

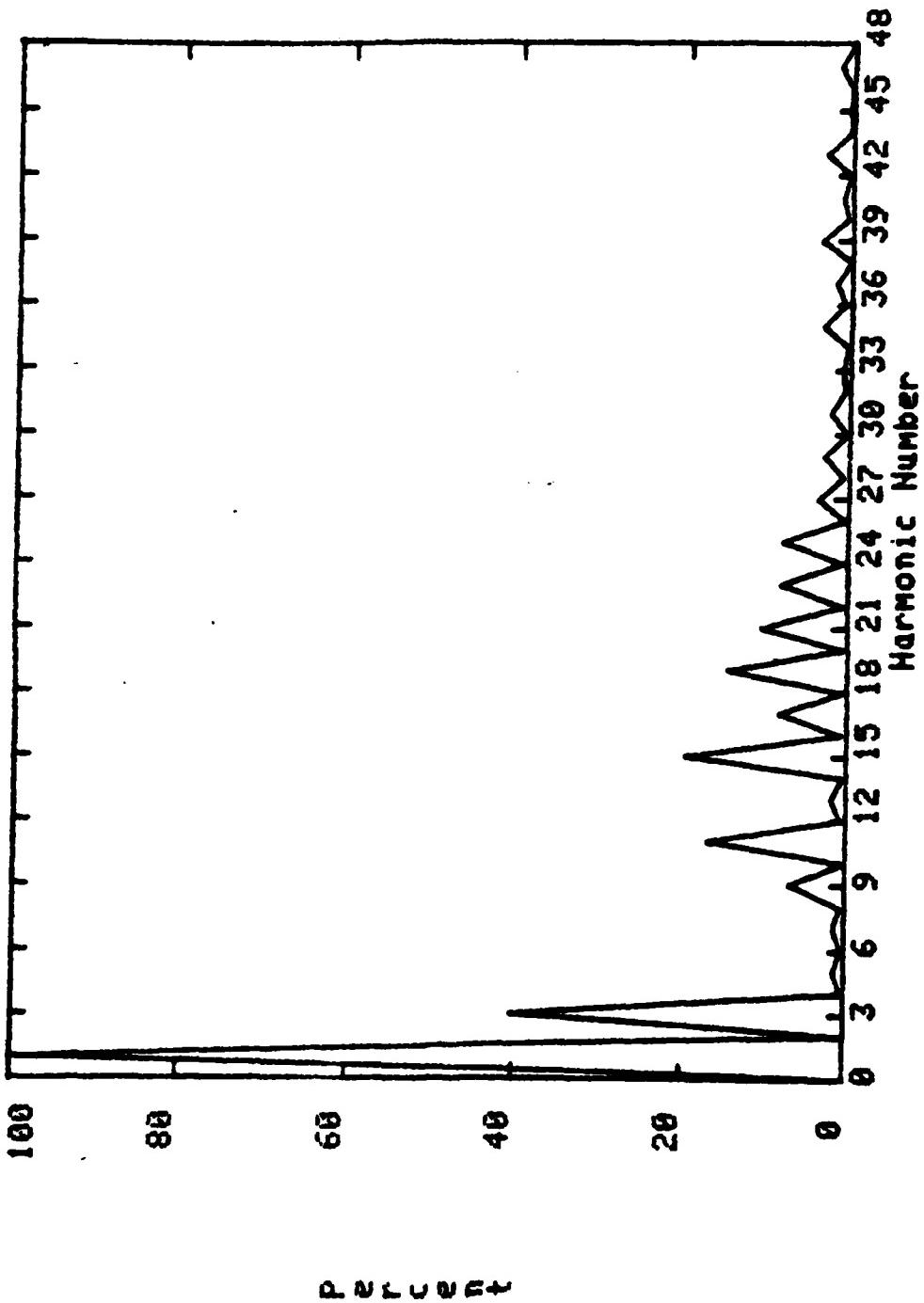


Figure 12. Fourier Spectrum of Phase Current - 4500 RPM, Fifth and Seventh Harmonics Eliminated

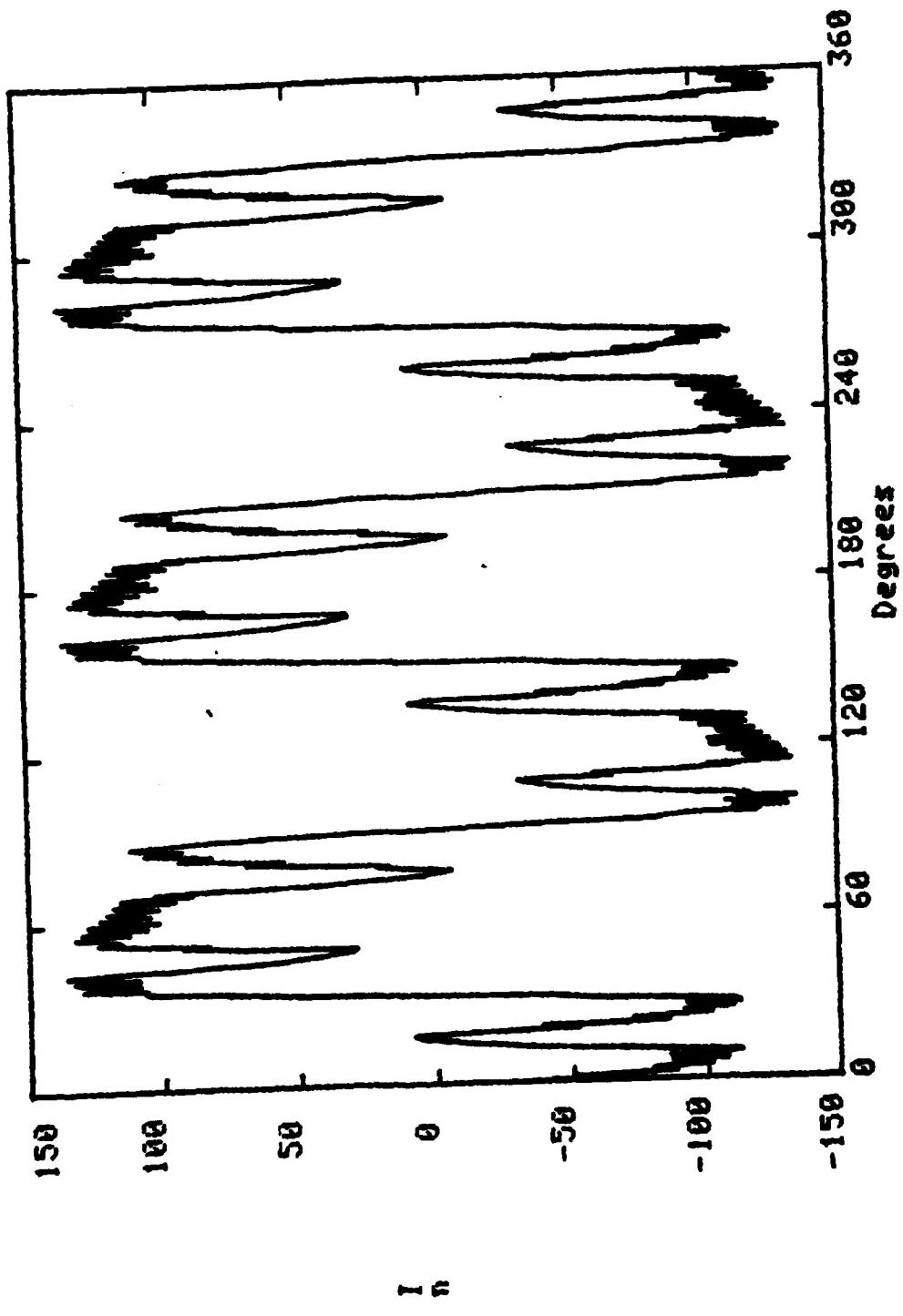


Figure 13. Neutral Current - 4500 RPM, Fifth and Seventh Harmonics Eliminated

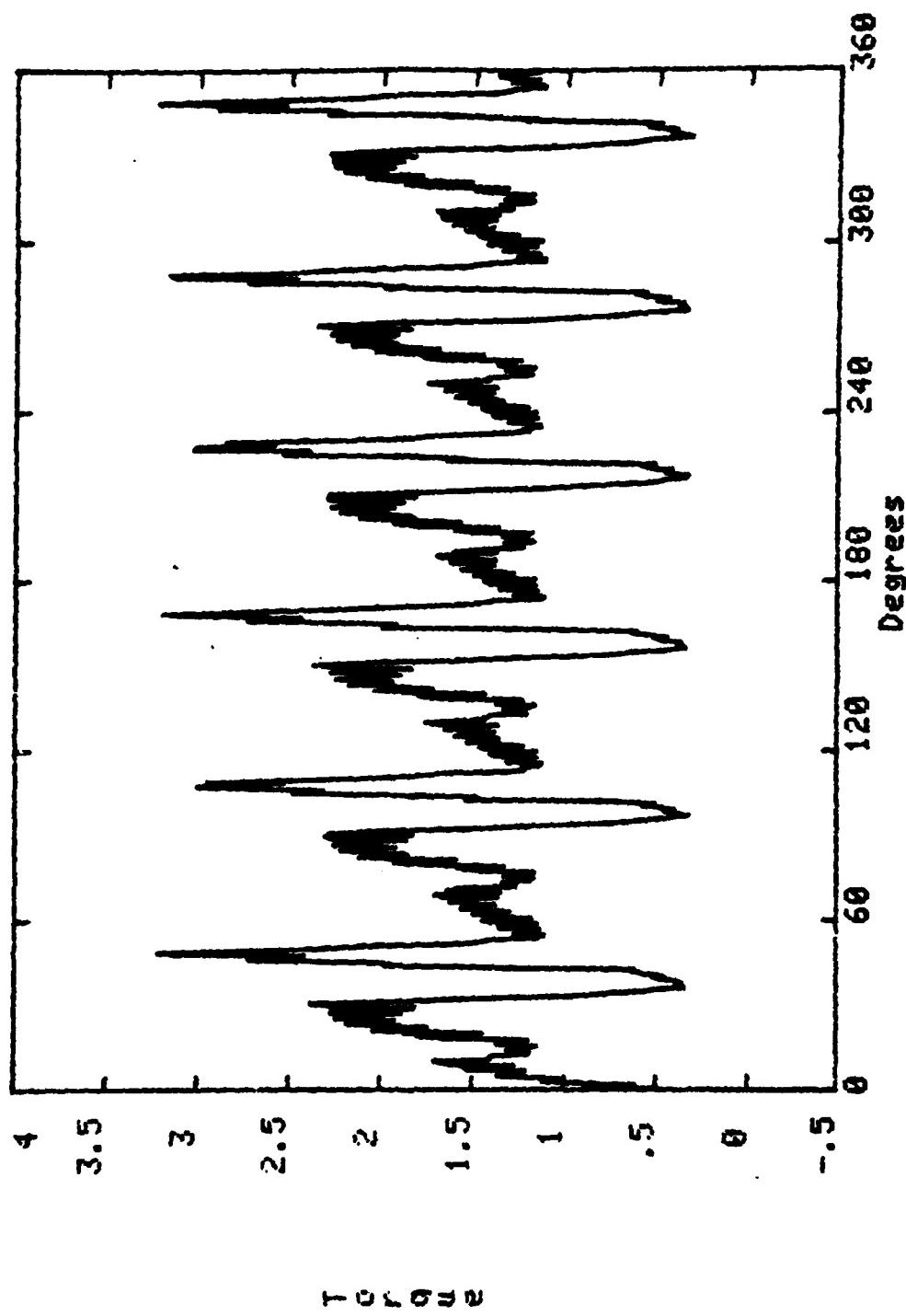


Figure 14. Developed Torque - 4500 RPM, Sixth Harmonic Eliminated

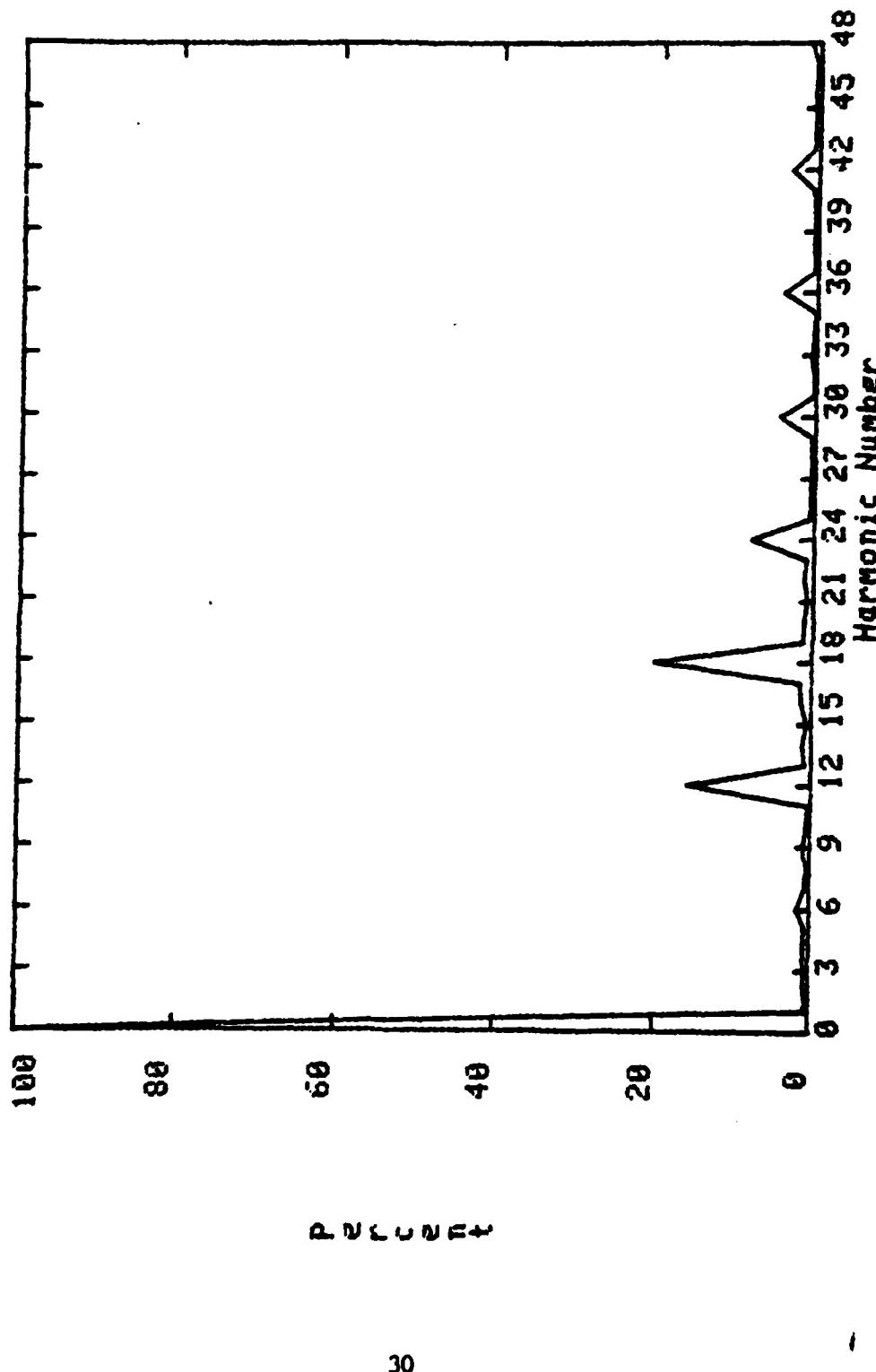


Figure 15. Fourier Spectrum of Developed Torque - 4500 RPM,  
Sixth Harmonic Eliminated

A plot of phase current  $i_1$  is given by Figure 16. The associated Fourier spectrum of  $i_1$  is shown by Figure 17 where negligibly small fifth, seventh, eleventh, and thirteenth harmonics are noted. Current flow through the neutral line is depicted by Figure 18.

A plot of the instantaneous developed torque is given by Figure 19. The Fourier spectrum of the developed torque is shown in Figure 20 where it is seen that the sixth and twelfth harmonics are near zero.

## 2.2 2250 RPM (5% Speed Case)

### 2.2.1 Unmodulated Phase Voltage.

#### Input Data

Motor speed,  $n_m$  = 2250 rpm  
Motor frequency,  $f$  = 75 Hz  
SCR firing angle,  $\alpha_s$  = 61.93°  
Specified average torque,  $T_{dav}$  = 1.5 N·m

#### Output Data

Average torque,  $T_{day}$  = 1.499 N·m  
RMS phase current,  $I_{RMS}$  = 69.53 A

A plot of phase current  $i_1$  is given by Figure 21. The associated Fourier spectrum of  $i_1$  is shown by Figure 22.

A plot of the instantaneous developed torque is given by Figure 23. A Fourier spectrum of the developed torque is shown by Figure 24.

### 2.2.2 Elimination of Sixth Harmonic of Torque. The sixth harmonic of torque is eliminated by removing the fifth and seventh harmonics of phase current.

#### Input Data

Motor speed,  $n_m$  = 2250 rpm  
Motor frequency,  $f$  = 75 Hz  
SCR firing angle,  $\alpha_s$  = 50.21°  
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  = 40.76°  
 $\alpha_2$  = 47.73°  
 $\alpha_3$  = 58.65°

#### Output Data

Average torque,  $T_{day}$  = 1.5001 N·m  
RMS phase current,  $I_{RMS}$  = 73.96 A

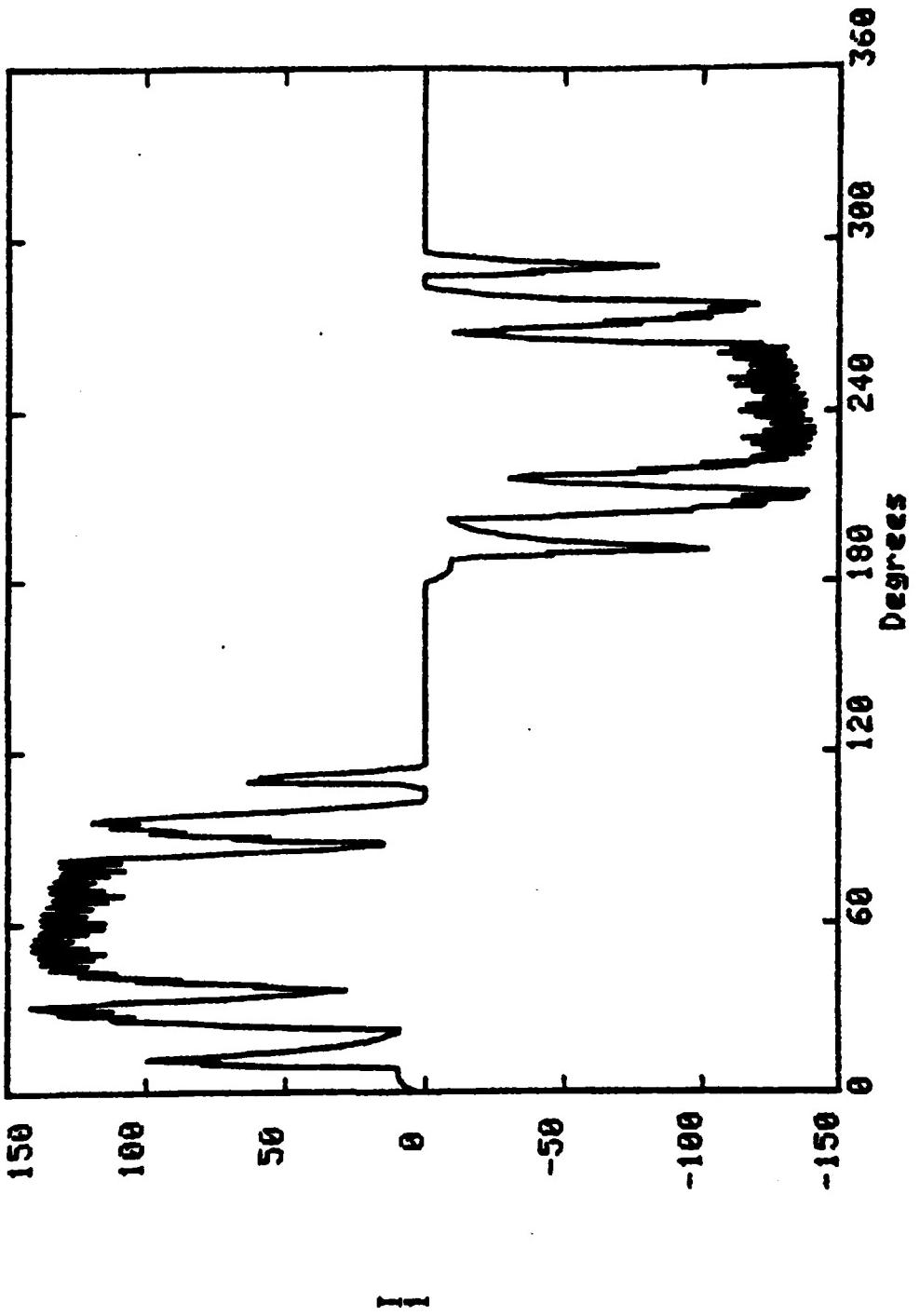


Figure 16. Phase Current - 4500 RPM, Fifth, Seventh, Eleventh and Thirteenth Harmonics Eliminated

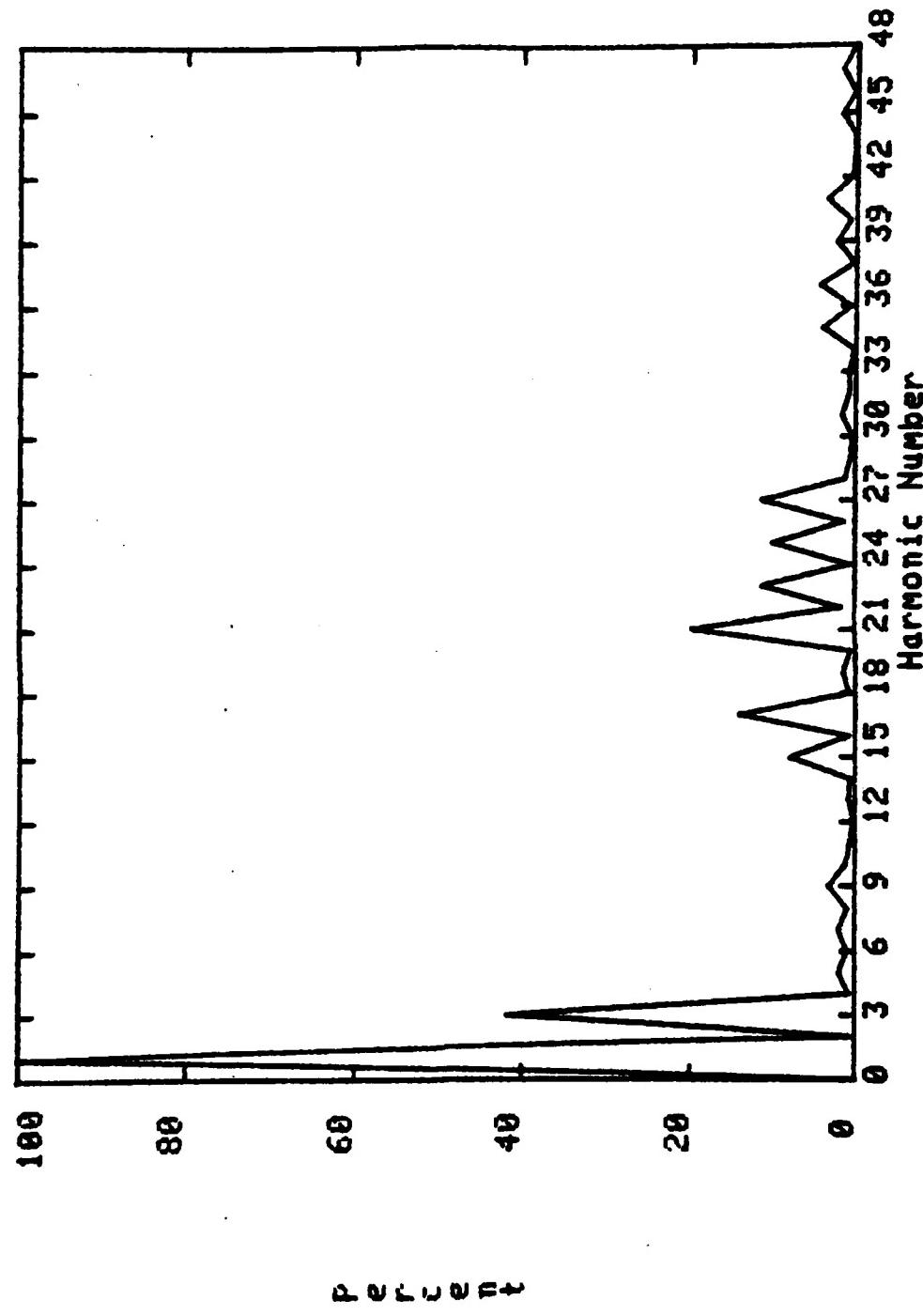


Figure 17. Fourier Spectrum of Phase Current - 4500 RPM, Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

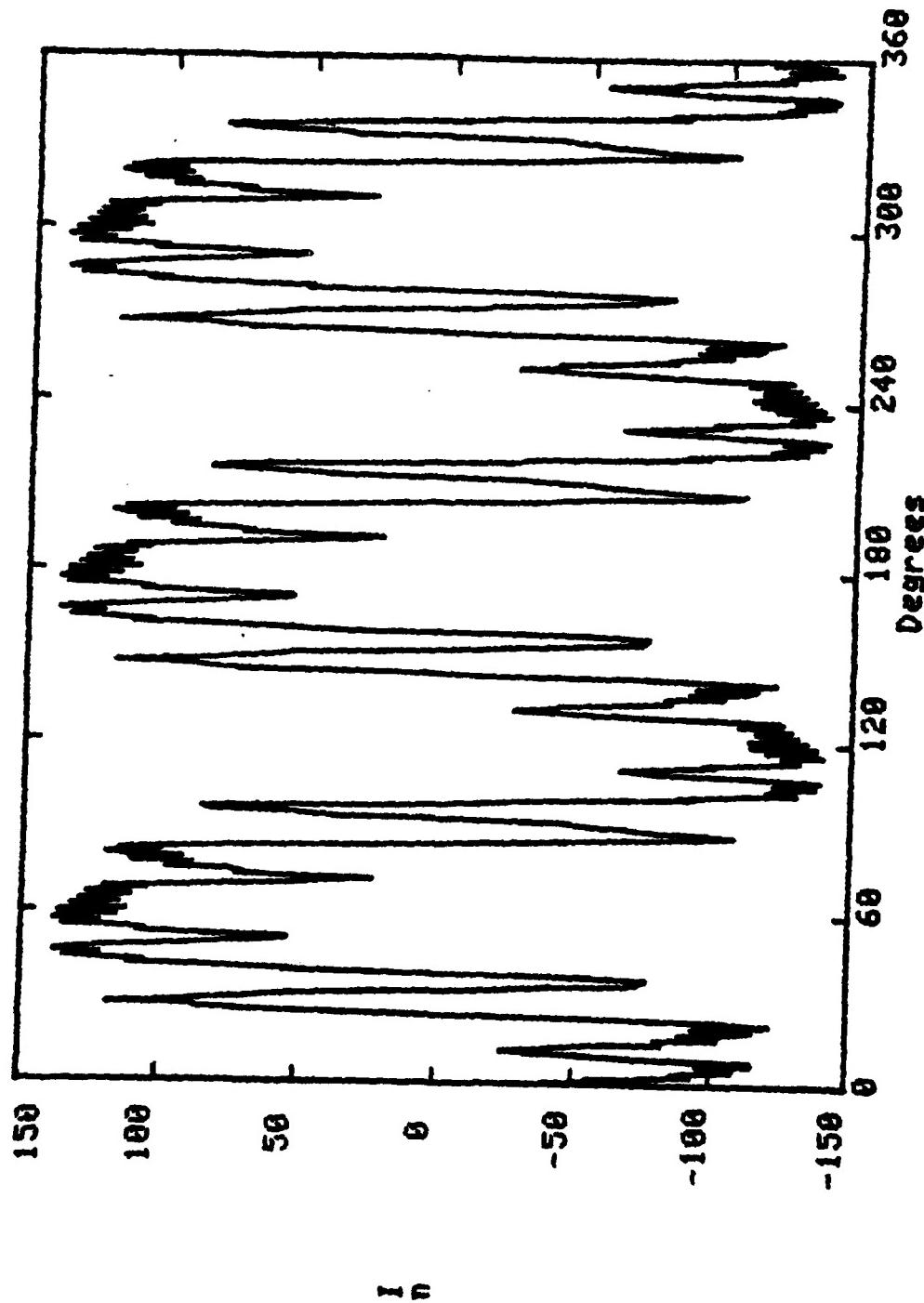


Figure 18. Neutral Current - 4500 RPM, Fifth, Seventh, Eleventh and Thirteenth Harmonics Eliminated

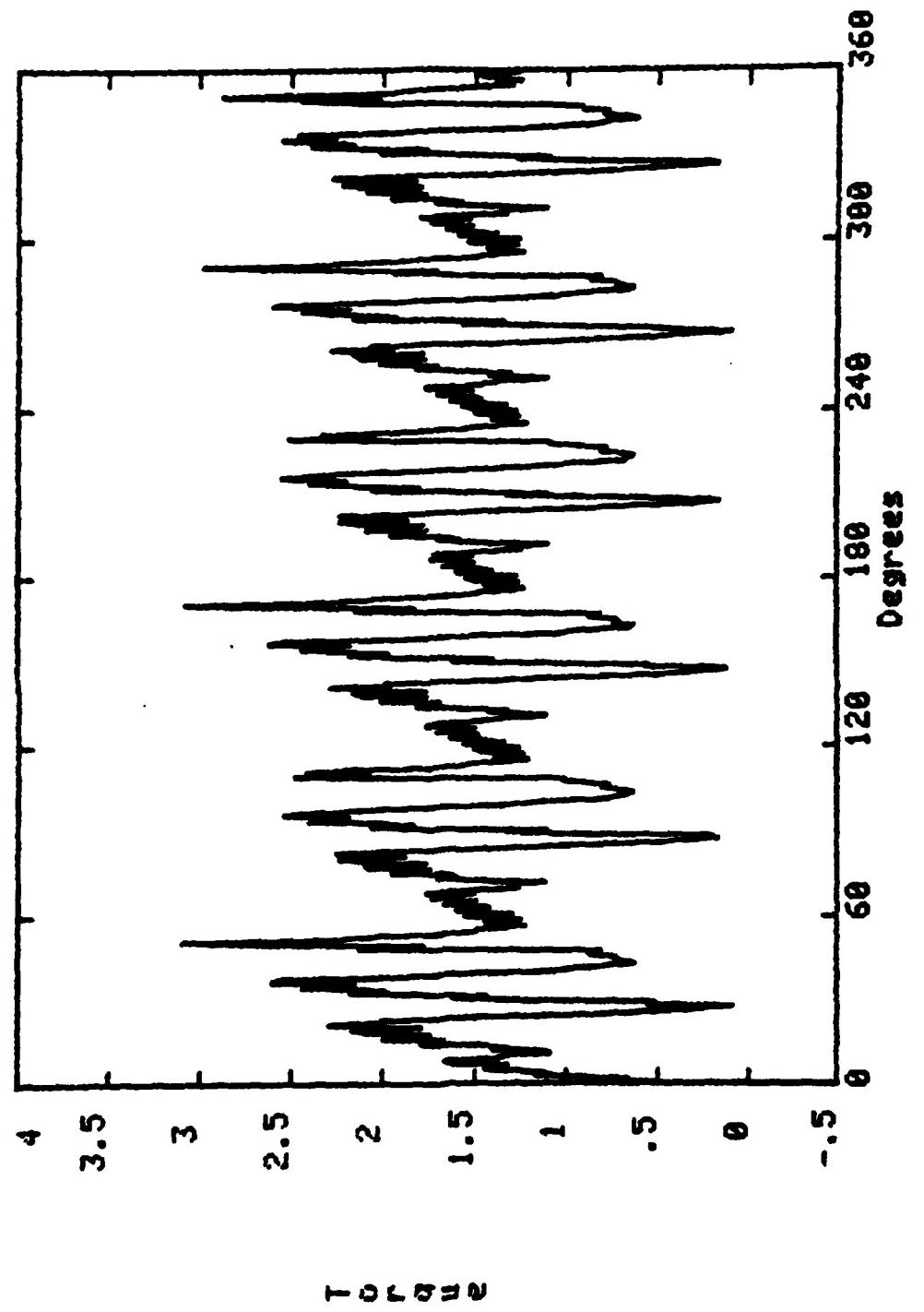


Figure 19. Developed Torque - 4500 RPM, Sixth and Twelfth Harmonics Eliminated

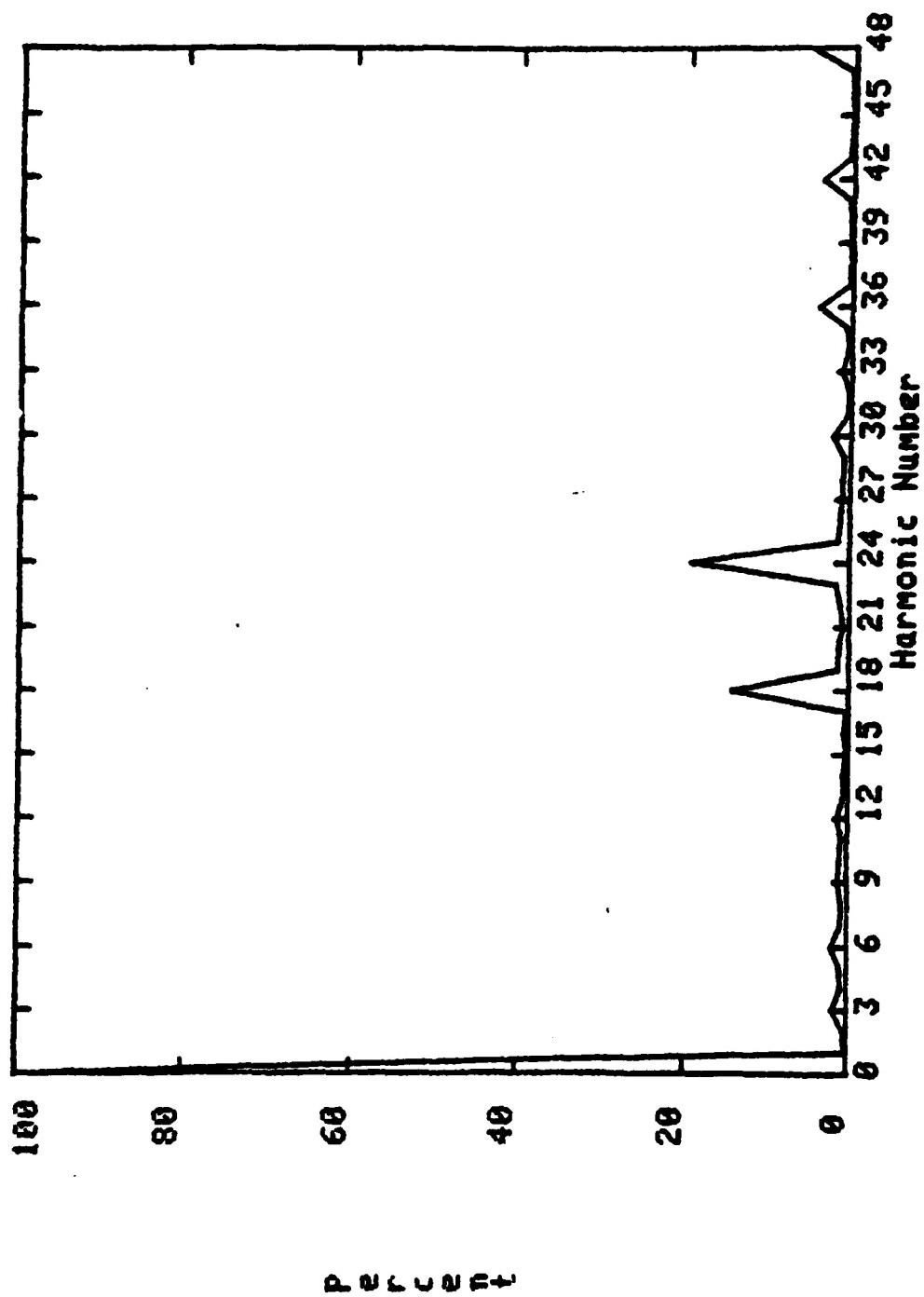


Figure 20. Fourier Spectrum of Developed Torque - 4500 RPM,  
Sixth and Twelfth Harmonics Eliminated

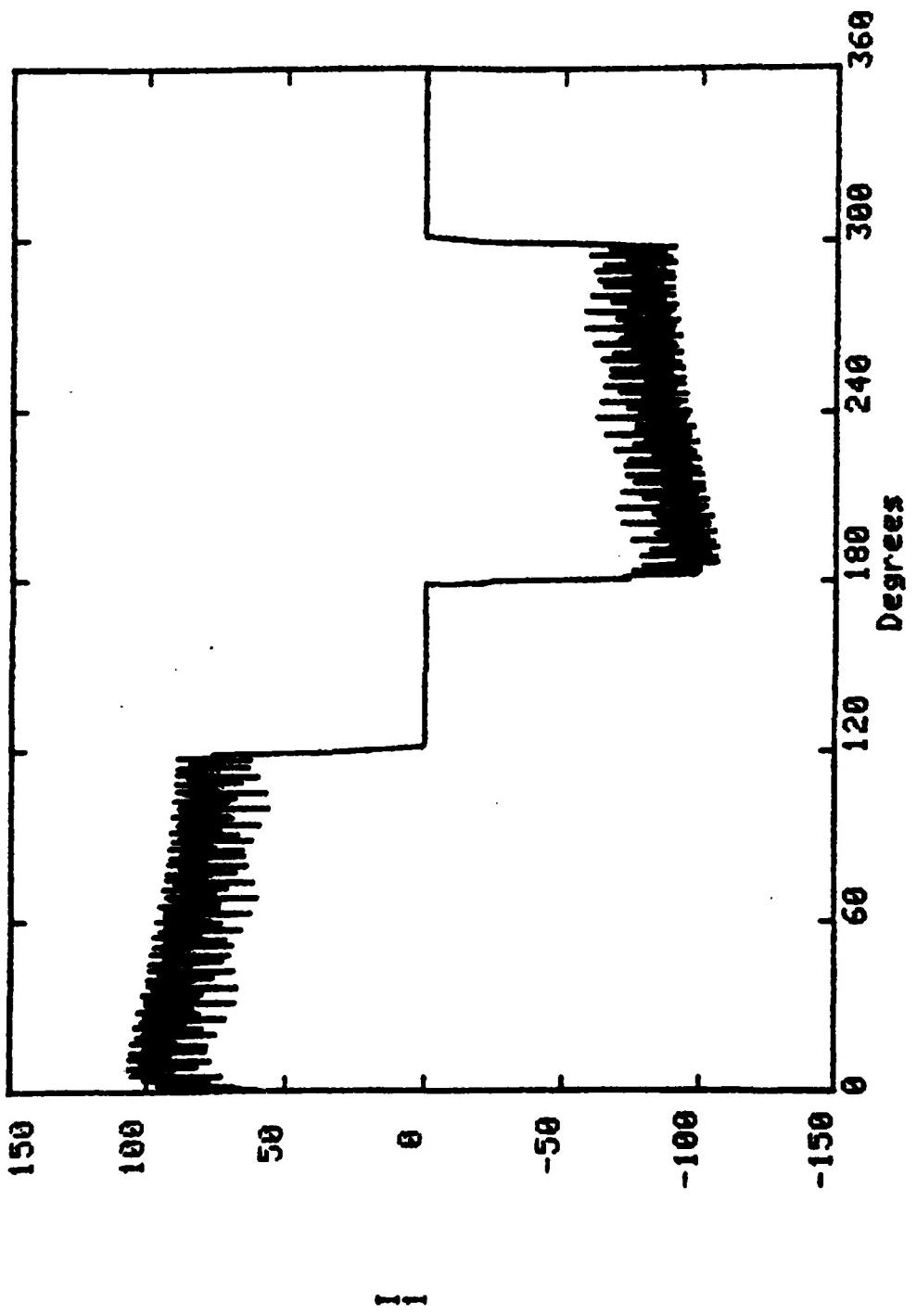


Figure 21. Phase Current - 2250 RPM, No Modulation

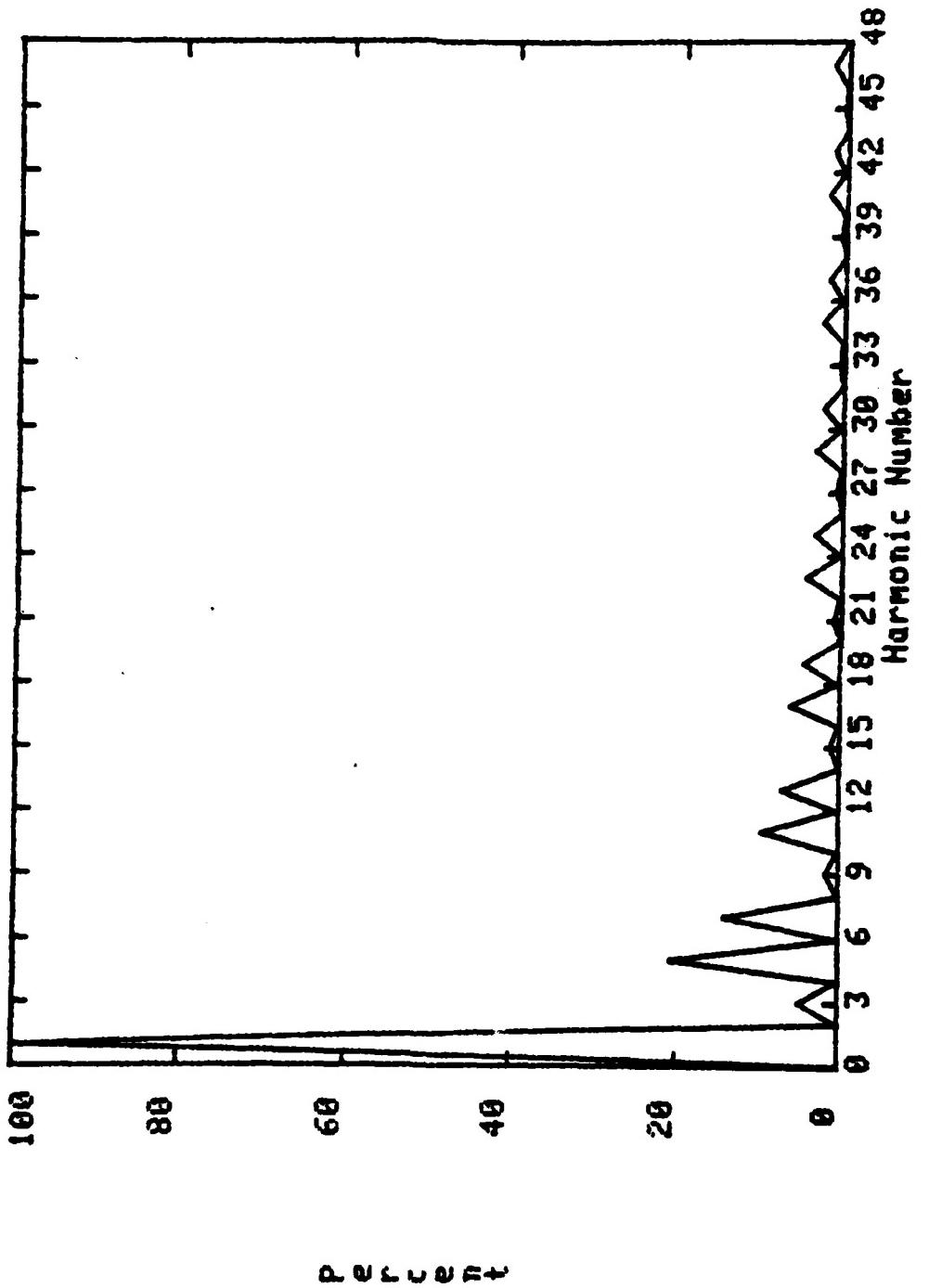


Figure 22. Fourier Spectrum of Phase Current - 2250 RPM, No Modulation

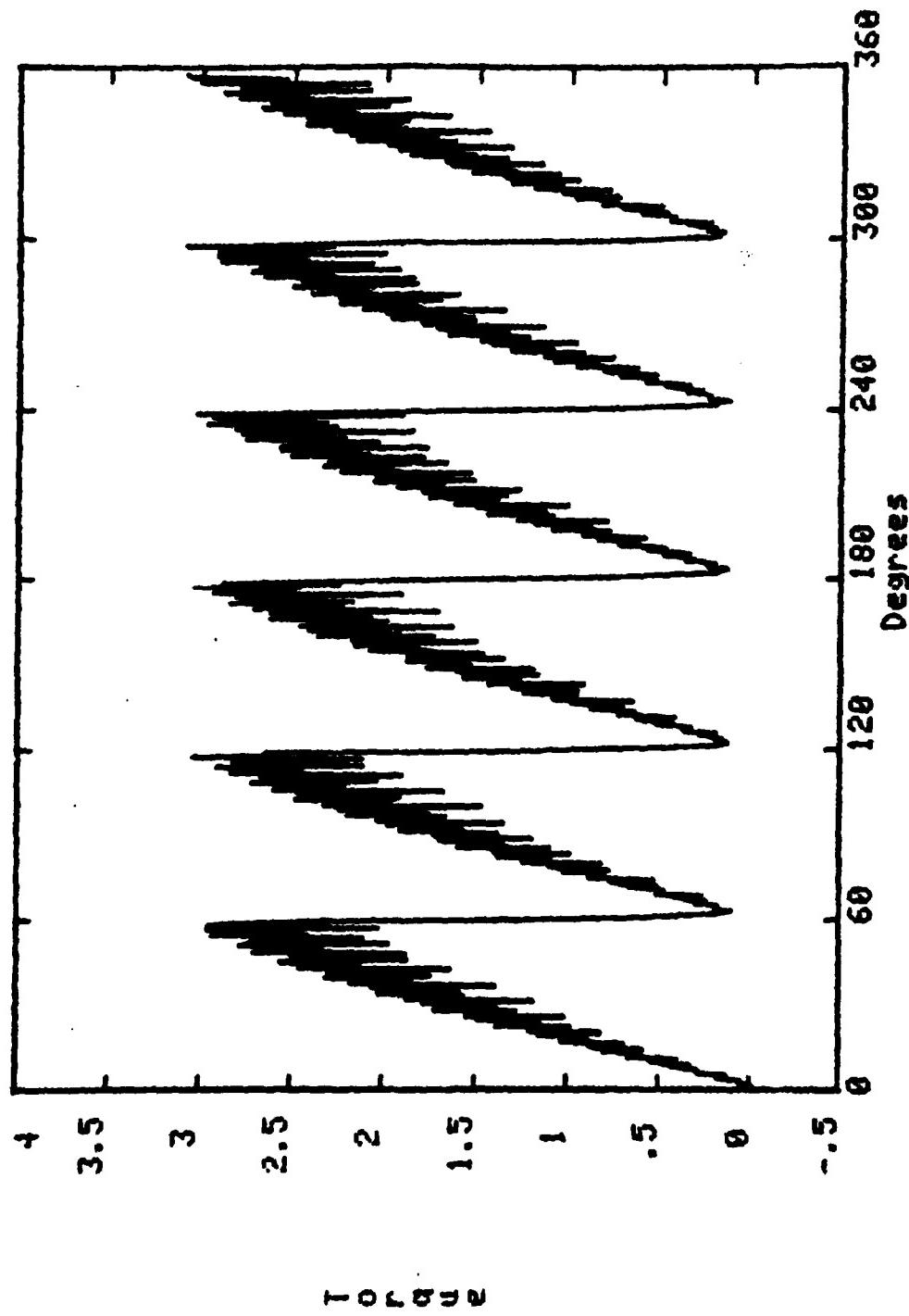


Figure 23. Developed Torque - 2250 RPM, No Modulation

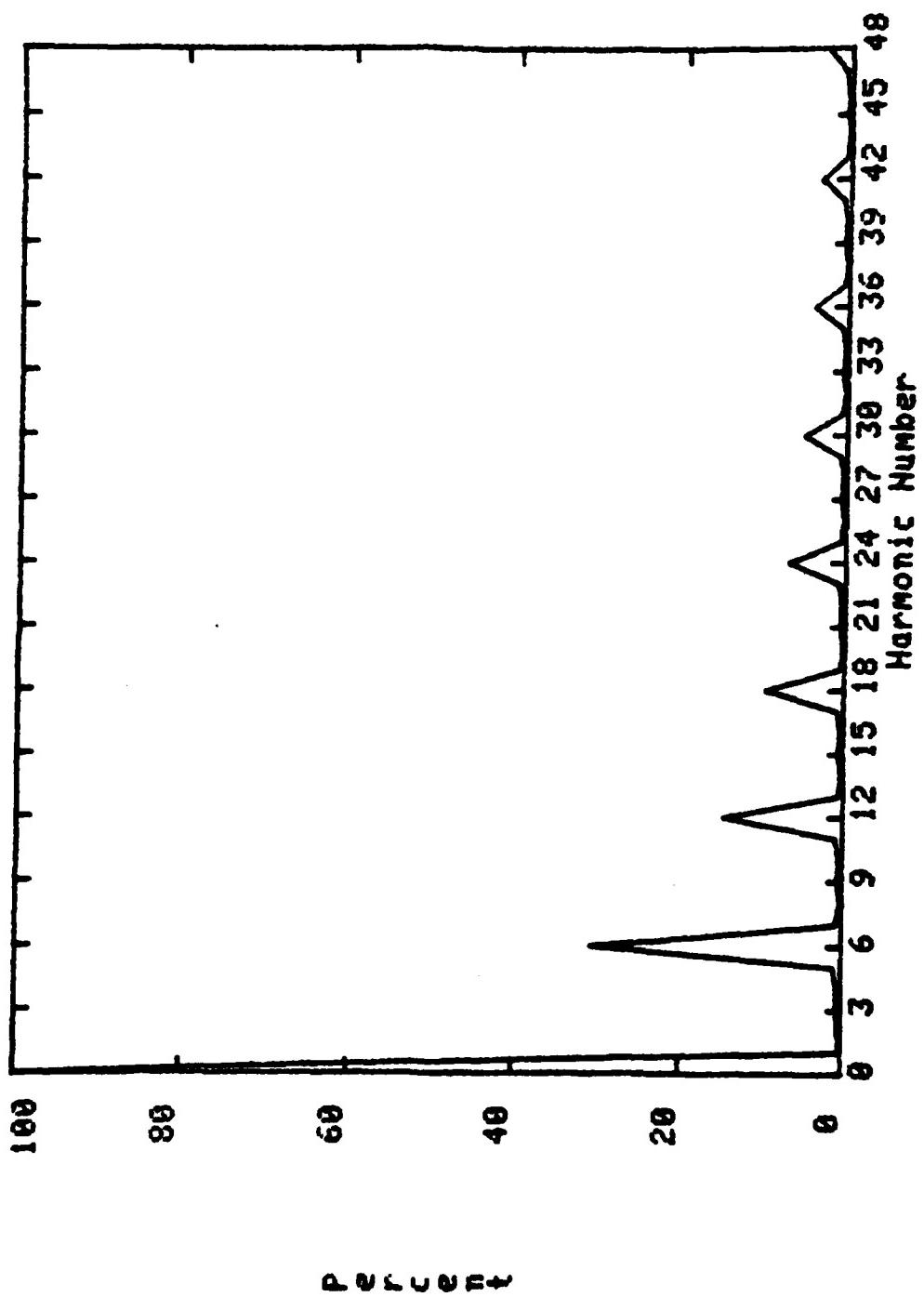


Figure 24. Fourier Spectrum of Developed Torque  $\approx$  2250 RPM, No Modulation

A plot of phase current  $i_1$  is given by Figure 25. The associated Fourier spectrum is shown by Figure 26.

A plot of the instantaneous developed torque is given by Figure 27. The Fourier spectrum of the developed torque is shown by Figure 28.

2.2.3 Elimination of Sixth and Twelfth Harmonics of Torque. Both the sixth and twelfth harmonics of torque are eliminated by removing the fifth, seventh, eleventh, and thirteenth harmonics of phase current.

#### Input Data

Motor speed,  $n_m$  = 2250 rpm  
Motor frequency,  $f$  = 75 Hz  
SCR firing angle,  $\alpha_s$  = 47.31°  
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  = 38.73°  
 $\alpha_2$  = 42.13°  
 $\alpha_3$  = 52.25°  
 $\alpha_4$  = 61.93°  
 $\alpha_5$  = 66.86°

#### Output Data

Average torque,  $T_{dav}$  = 1.5003 N·m  
RMS phase current,  $I_{RMS}$  = 74.64 A

A plot of phase current  $i_1$  is given by Figure 29. The associated Fourier spectrum of  $i_1$  is shown by Figure 30.

A plot of the instantaneous developed torque is given by Figure 31. The Fourier spectrum of the developed torque is shown by Figure 32.

2.2.4 Elimination of Sixth and Twelfth Harmonics of Torque ( $\alpha = 15^\circ$ ). The angle from the onset of positive phase current to the positive going crossing of the associated motor phase counter emf is changed from 30° to 15° to examine effect on current harmonics.

#### Input Data

Motor speed,  $n_m$  = 2250 rpm  
Motor frequency,  $f$  = 75 Hz  
SCR firing angle,  $\alpha_s$  = 59.84°  
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  = 38.73°  
 $\alpha_2$  = 42.13°  
 $\alpha_3$  = 52.25°  
 $\alpha_4$  = 61.93°  
 $\alpha_5$  = 38.73°

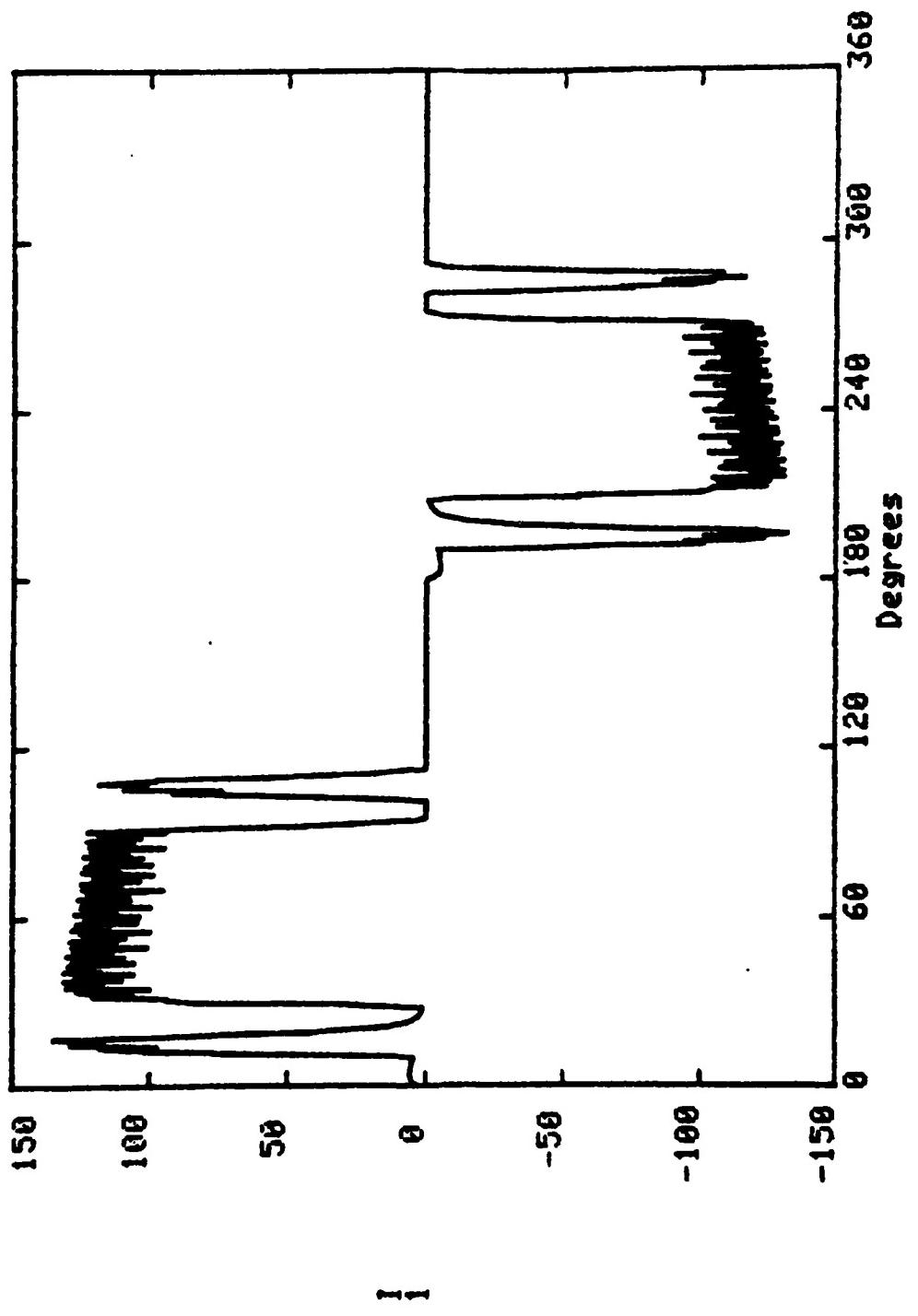


Figure 25. Phase Current - 2250 RPM, Fifth and Seventh Harmonics Eliminated

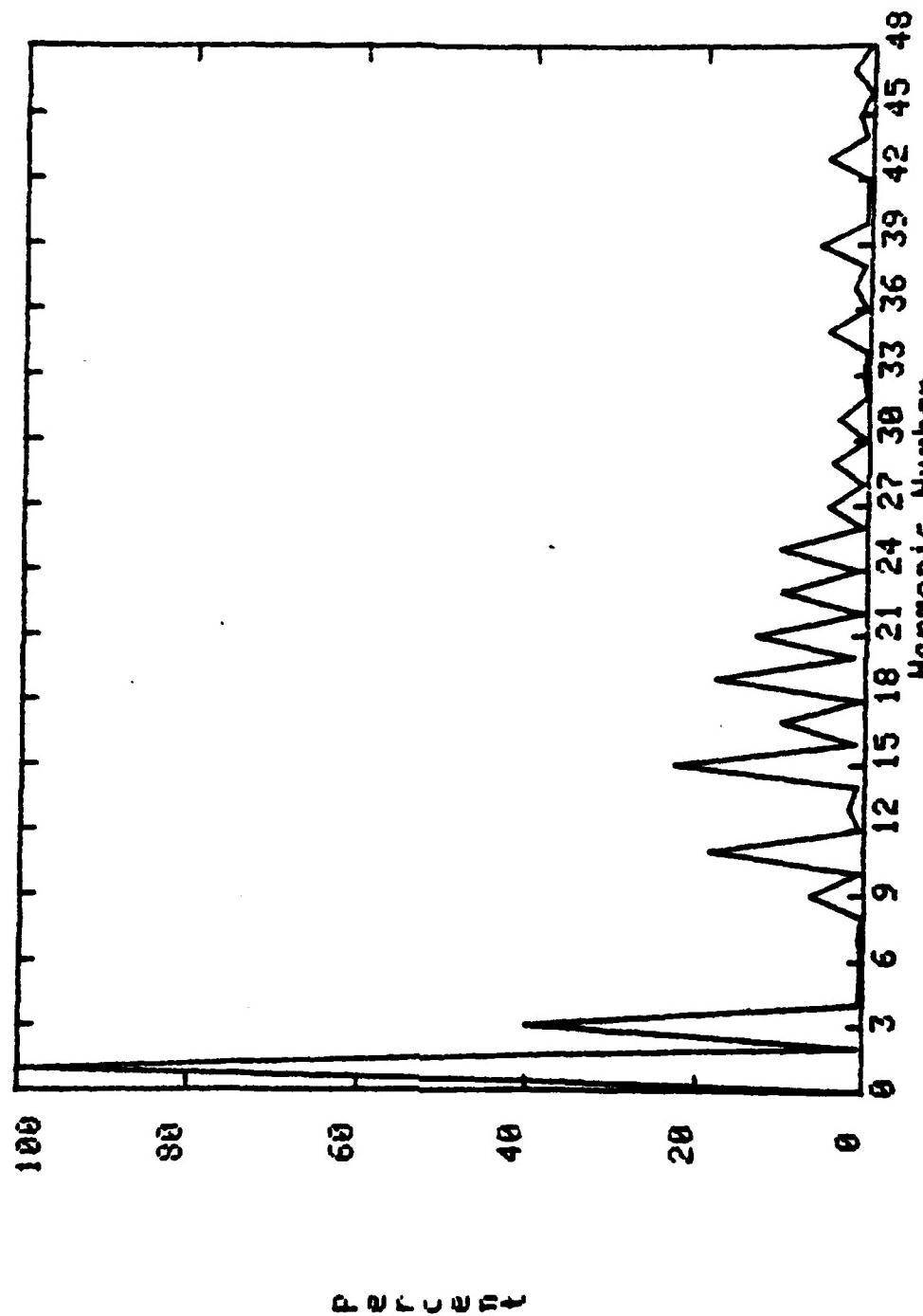


Figure 26. Fourier Spectrum of Phase Current - 2250 RPM, Fifth and Seventh Harmonics Eliminated

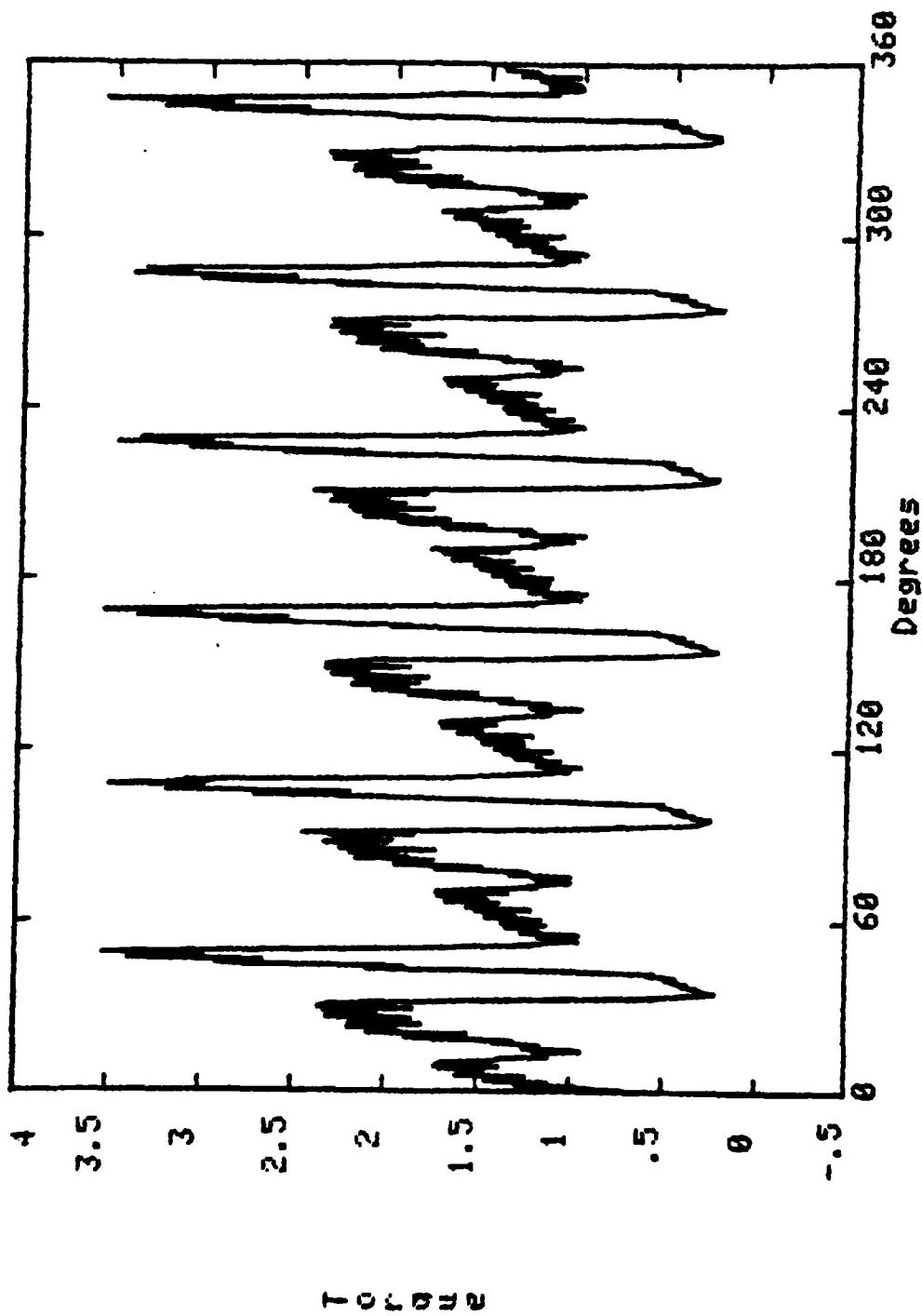


Figure 27. Developed Torque - 2250 RPM, Sixth Harmonic Eliminated

T O R Q U E

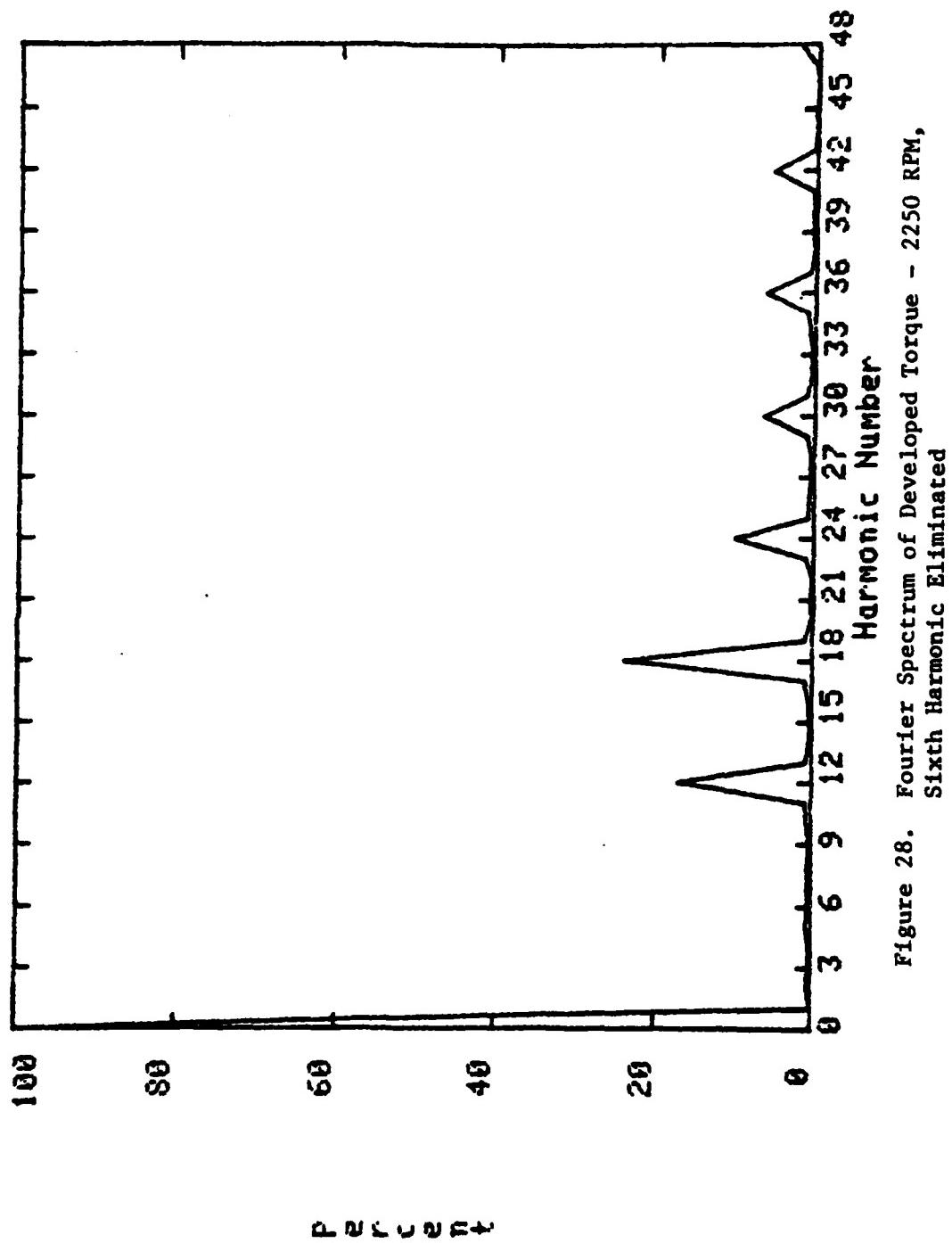


Figure 28. Fourier Spectrum of Developed Torque - 2250 RPM,  
Sixth Harmonic Eliminated

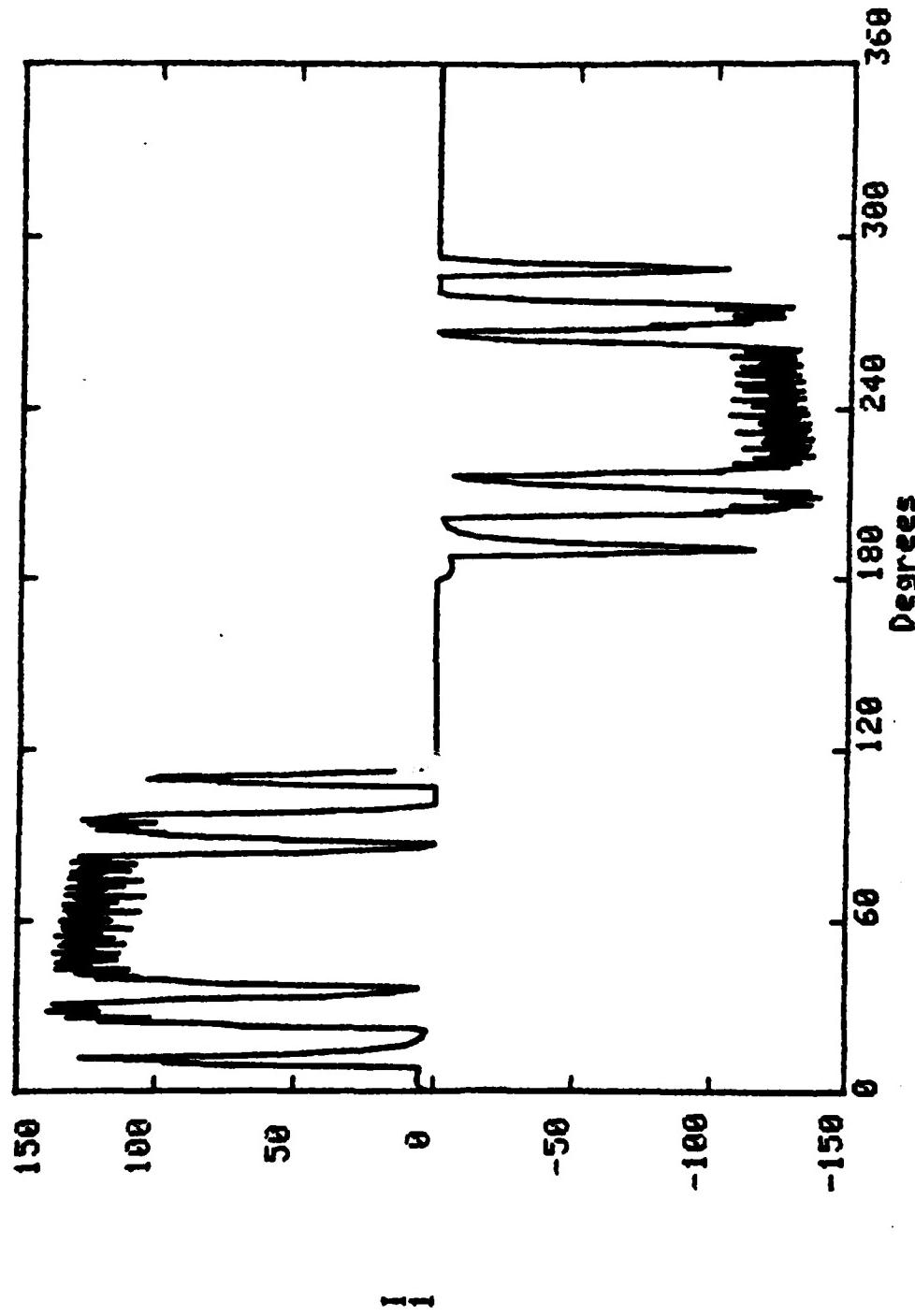


Figure 29. Phase Current - 2250 RPM, Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

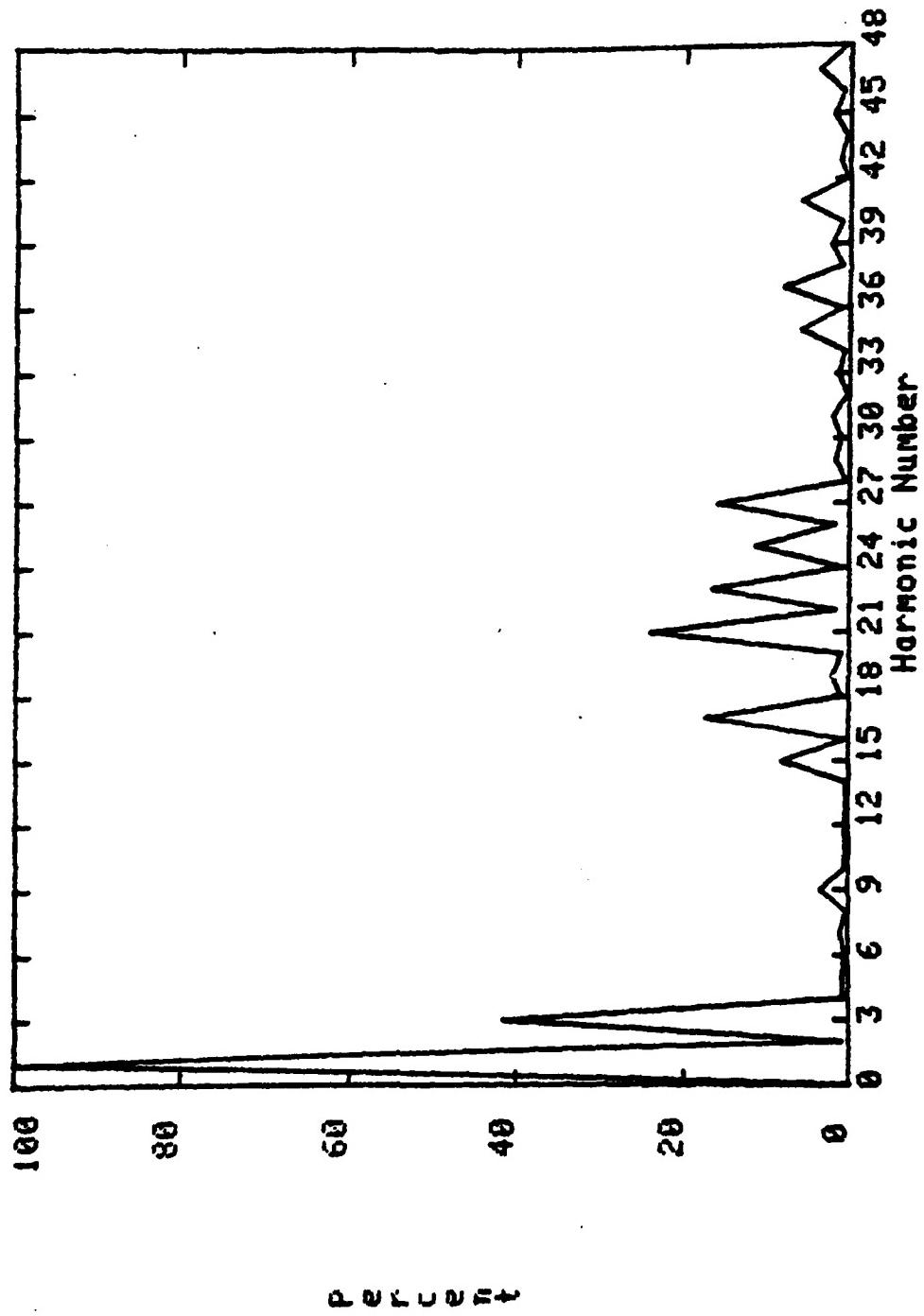


Figure 30. Fourier Spectrum of Phase Current - 2250 RPM, Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

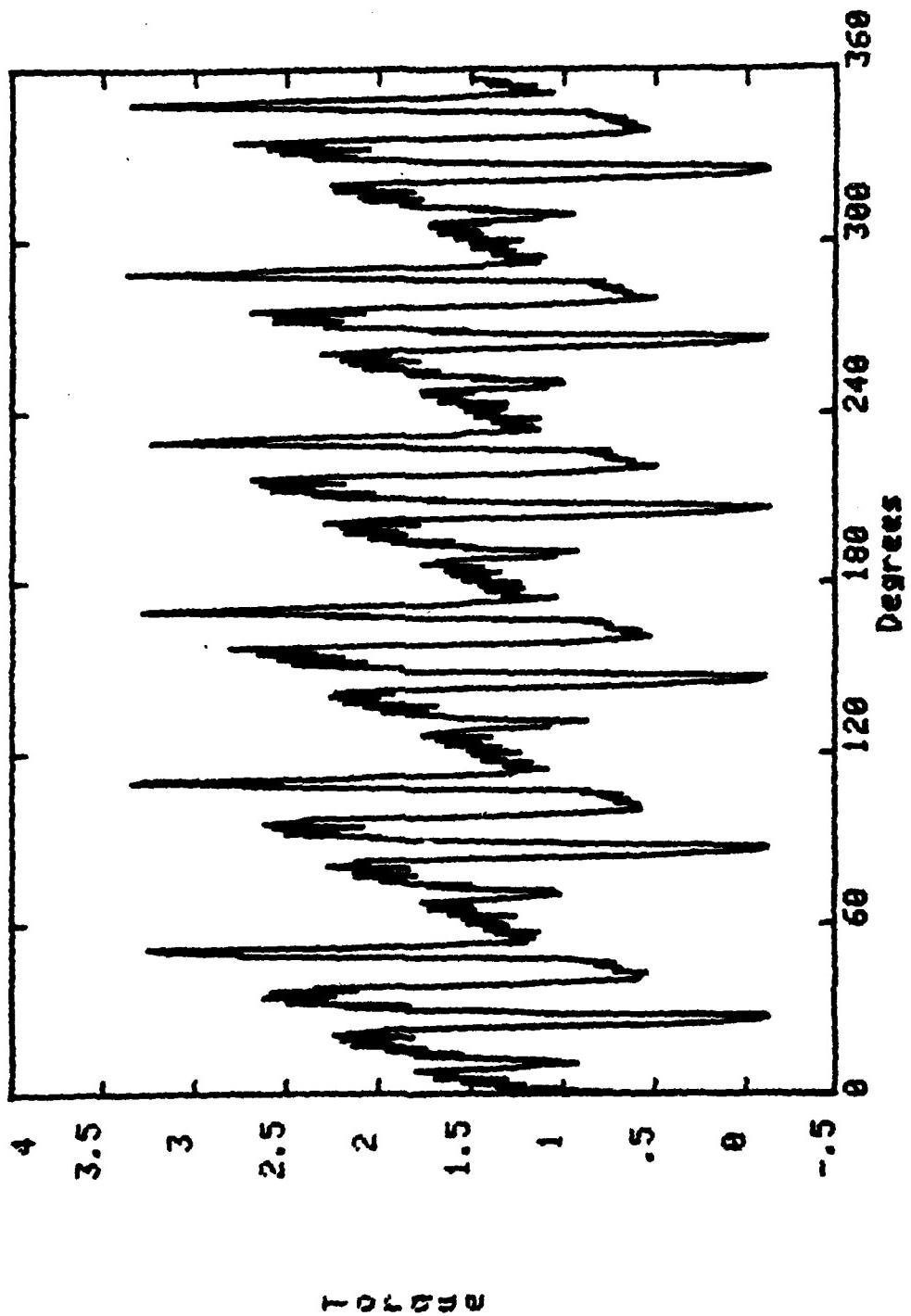


Figure 31. Developed Torque - 2250 RPM, Sixth and Twelfth Harmonics Eliminated

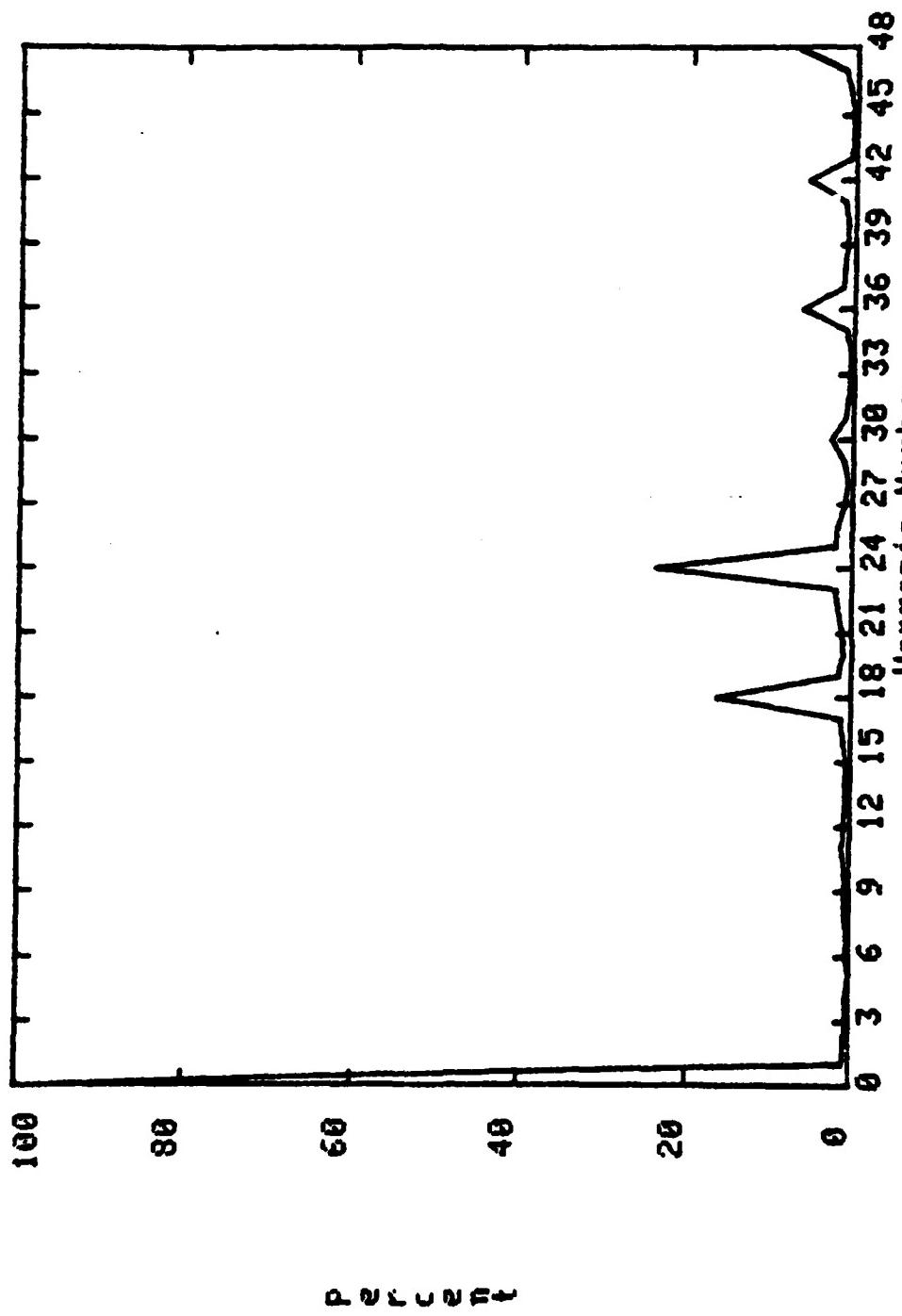


Figure 32. Fourier Spectrum of Developed Torque - 2250 RPM,  
Sixth and Twelfth Harmonics Eliminated

Output Data

Average torque,  $T_{dav} = 1.502 \text{ N}\cdot\text{m}$   
RMS phase current,  $I_{RMS} = 53.33 \text{ A}$

A plot of phase current  $i_1$  is given by Figure 33. The associated Fourier spectrum is shown by Figure 34.

A plot of instantaneous developed torque is given by Figure 35. The Fourier spectrum of the developed torque is shown by Figure 36.

The re-introduced harmonic magnitudes are reduced to a lower level than for  $\alpha = 30^\circ$ .

**2.2.5 Elimination of Sixth and Twelfth Harmonics of Torque ( $\alpha = 40^\circ$ ).**  
The angle from onset of positive phase current to the positive going crossing of the associated motor phase counter emf is set at  $40^\circ$  to examine the effect on current harmonics.

Input Data

Motor speed,  $n_m = 2250 \text{ rpm}$   
Motor frequency,  $f = 75 \text{ Hz}$   
SCR firing angle,  $\alpha_s = 16.77^\circ$   
Specified average torque,  $T_{dav} = 1.5 \text{ N}\cdot\text{m}$   
Angles of modulation function,  $\alpha_1 = 38.73^\circ$   
 $\alpha_2 = 42.13^\circ$   
 $\alpha_3 = 52.25^\circ$   
 $\alpha_4 = 61.93^\circ$   
 $\alpha_5 = 66.86^\circ$

Output Data

Average torque,  $T_{dav} = 1.5003 \text{ N}\cdot\text{m}$   
RMS phase current,  $I_{RMS} = 107.52$

A plot of phase current  $i_1$  is given by Figure 37. The associated Fourier spectrum of phase current is shown by Figure 38.

A plot of instantaneous developed torque is given by Figure 39. The Fourier spectrum of developed torque is shown by Figure 40.

Although the angle power factor angle ( $\alpha + 30^\circ$ ) has been extended to  $75^\circ$  resulting in a large current to maintain the same power flow, no significant re-introduction of undesired harmonics is noted.

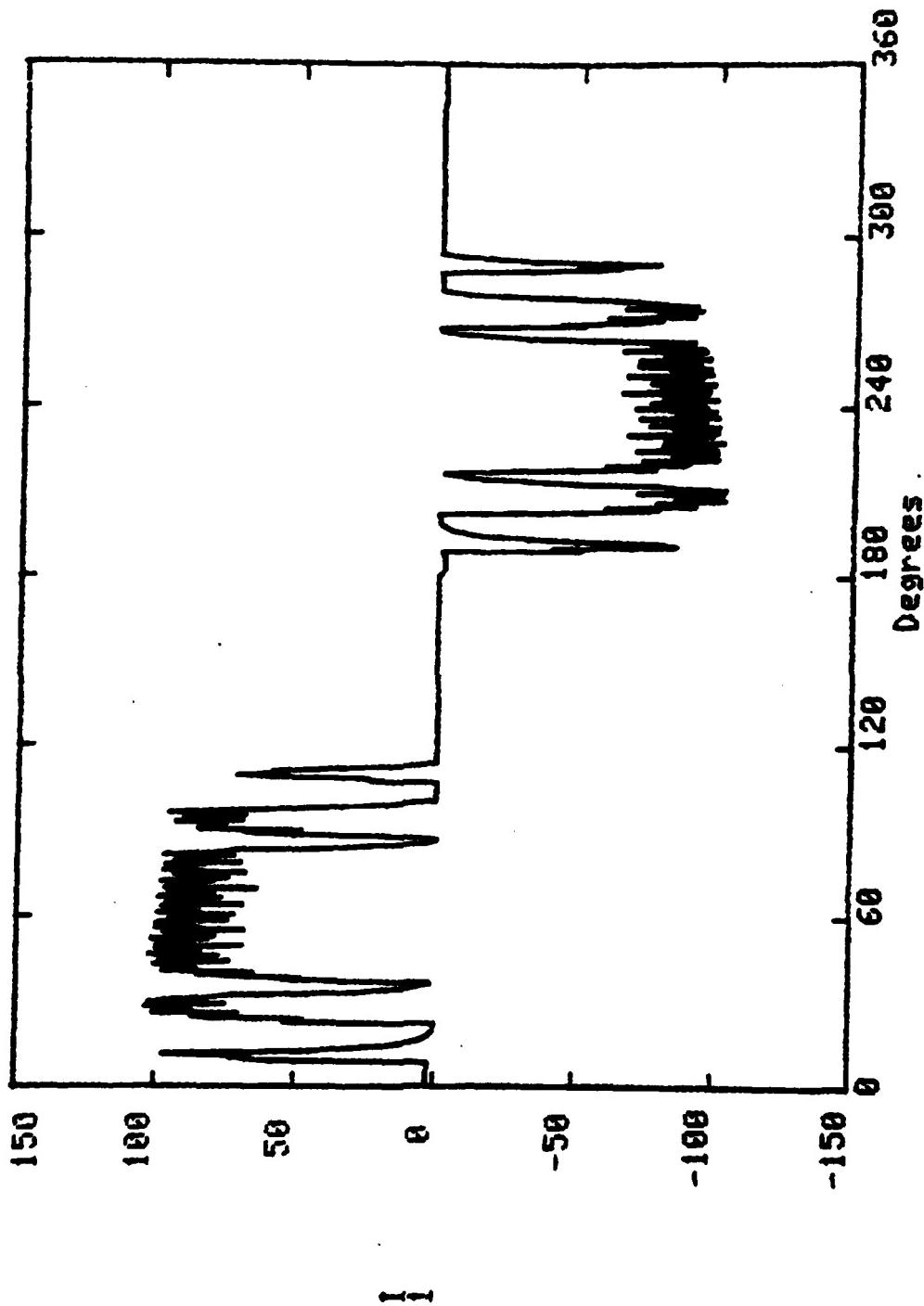


Figure 33. Phase Current - 2250 RPM,  $\alpha = 15^\circ$ , Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

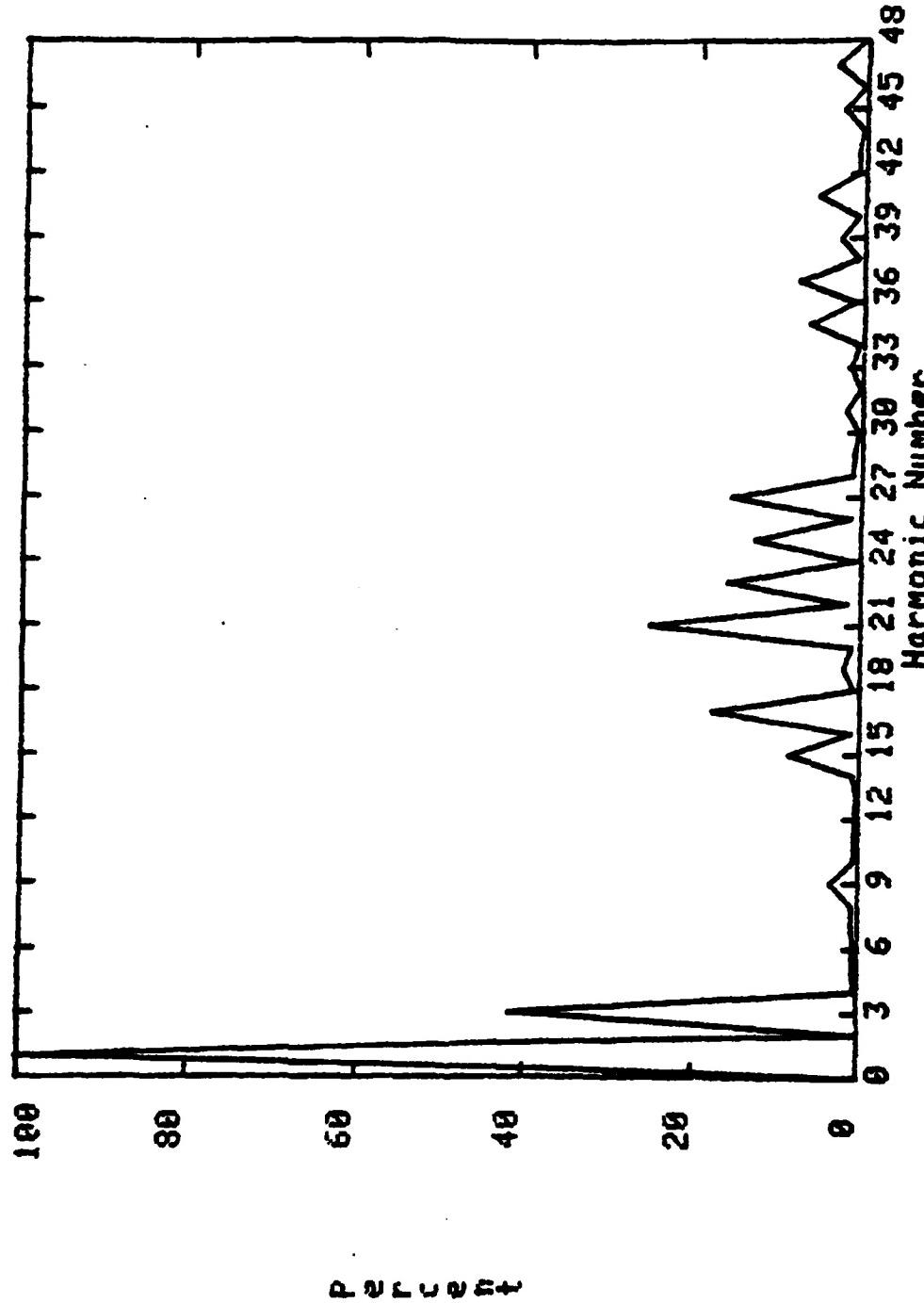
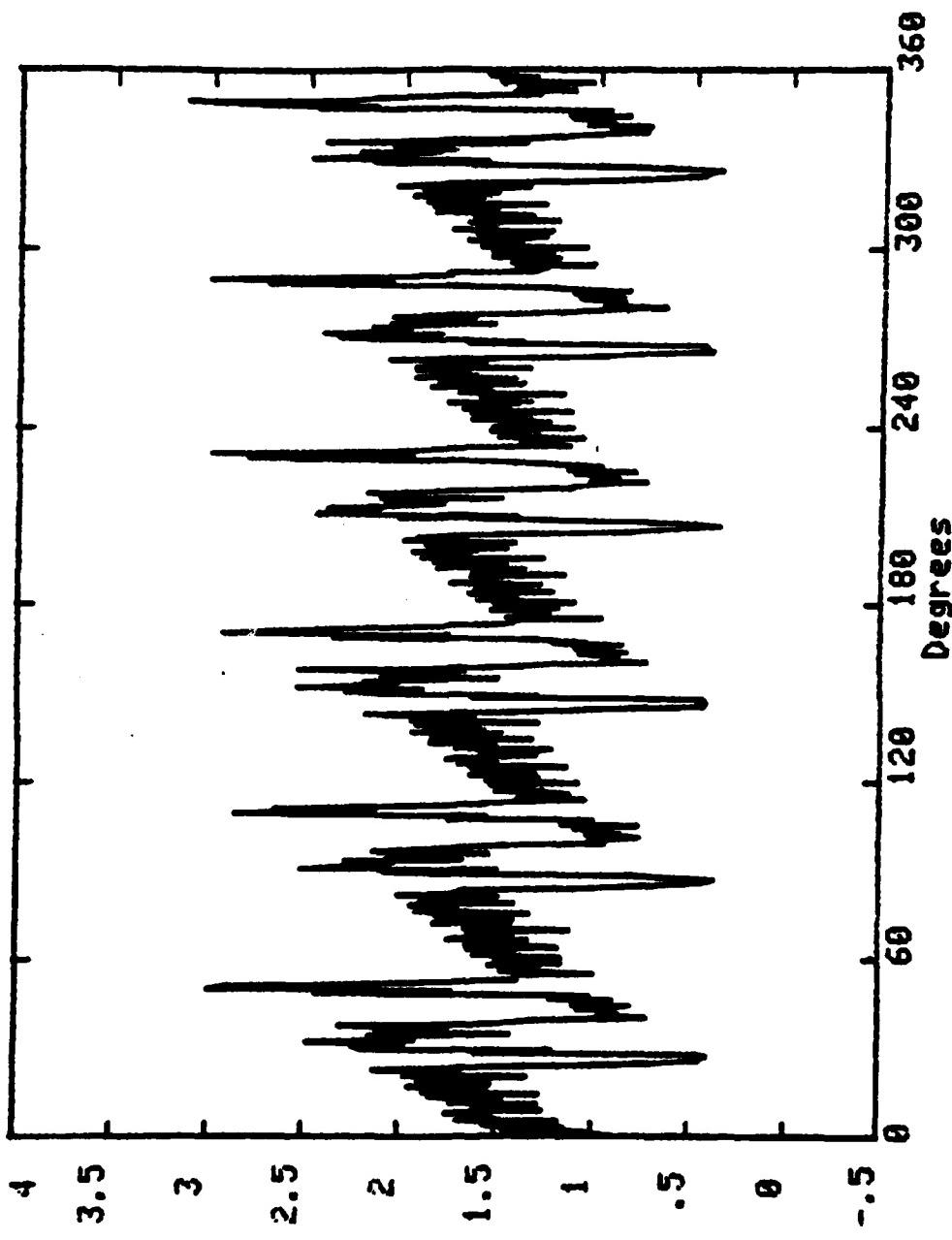


Figure 34. Fourier Spectrum of Phase Current - 2250 RPM,  $\alpha = 15^\circ$ ,  
Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated



TO RQUE

Figure 35. Developed Torque - 2250 RPM,  $\alpha = 15^\circ$ , Sixth and Twelfth Harmonics Eliminated

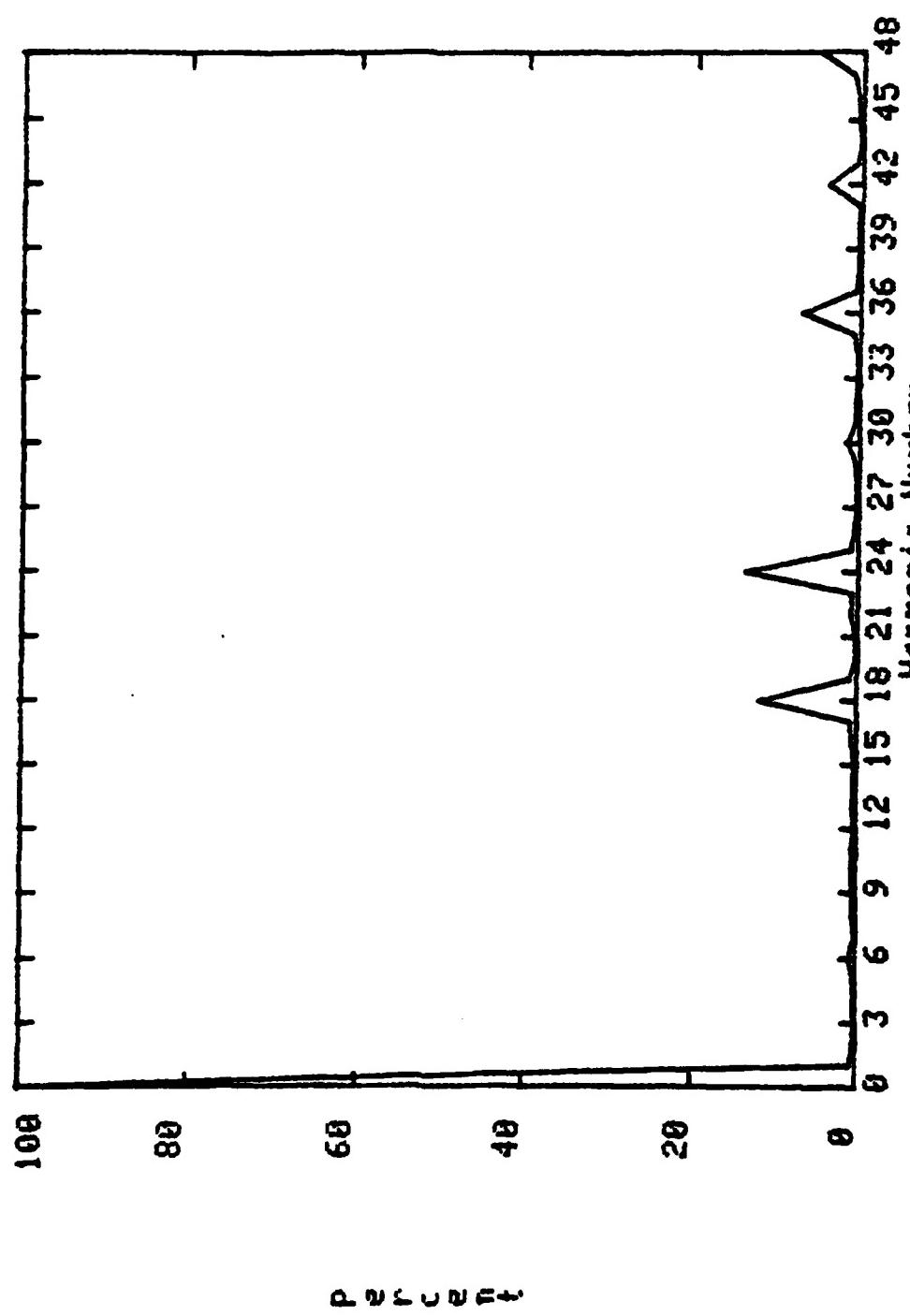


Figure 36. Fourier Spectrum of Developed Torque - 2250 RPM,  $\alpha = 15^\circ$ ,  
Sixth and Twelfth Harmonics Eliminated

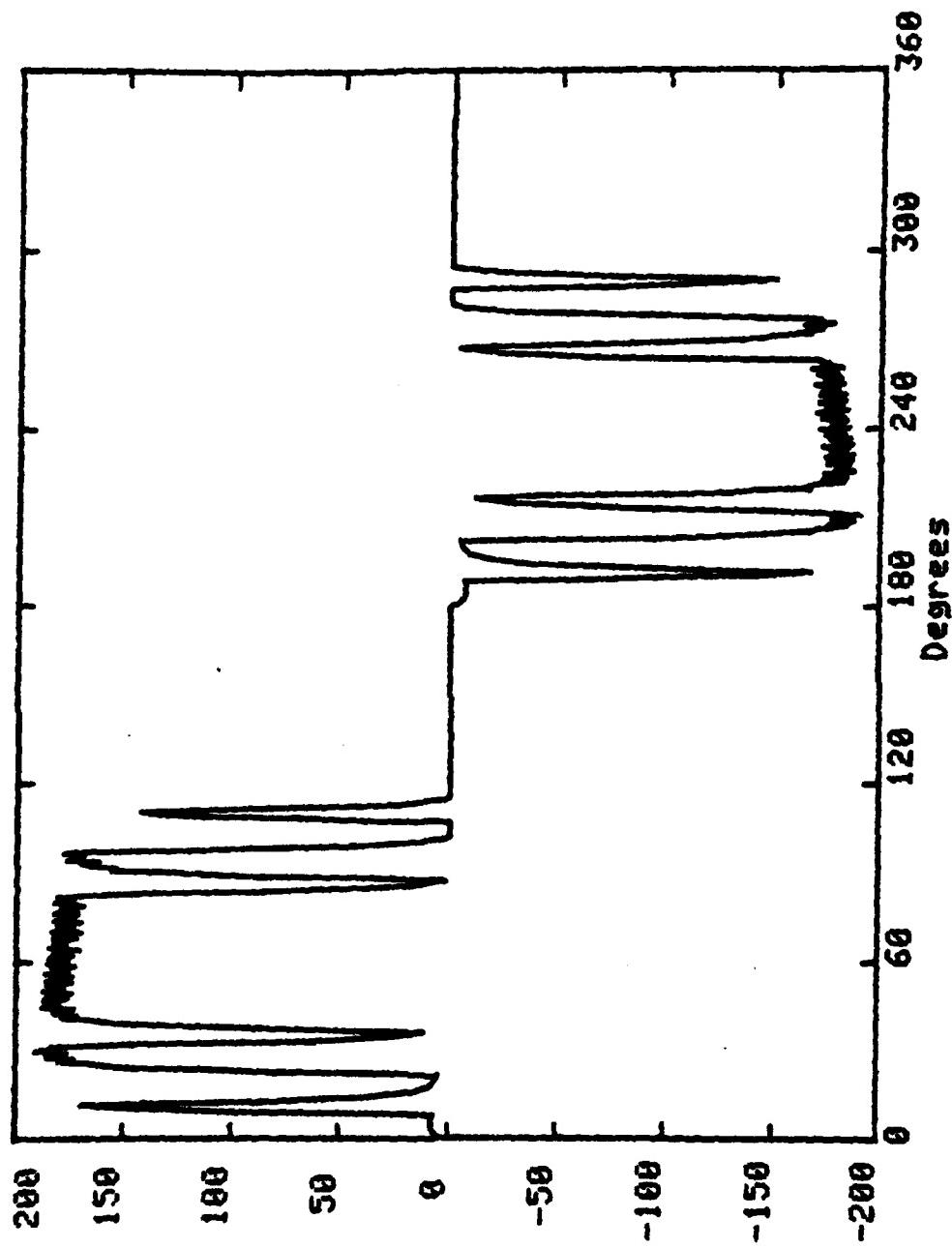


Figure 37. Phase Current - 2250 RPM,  $\alpha = 40^\circ$ , Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

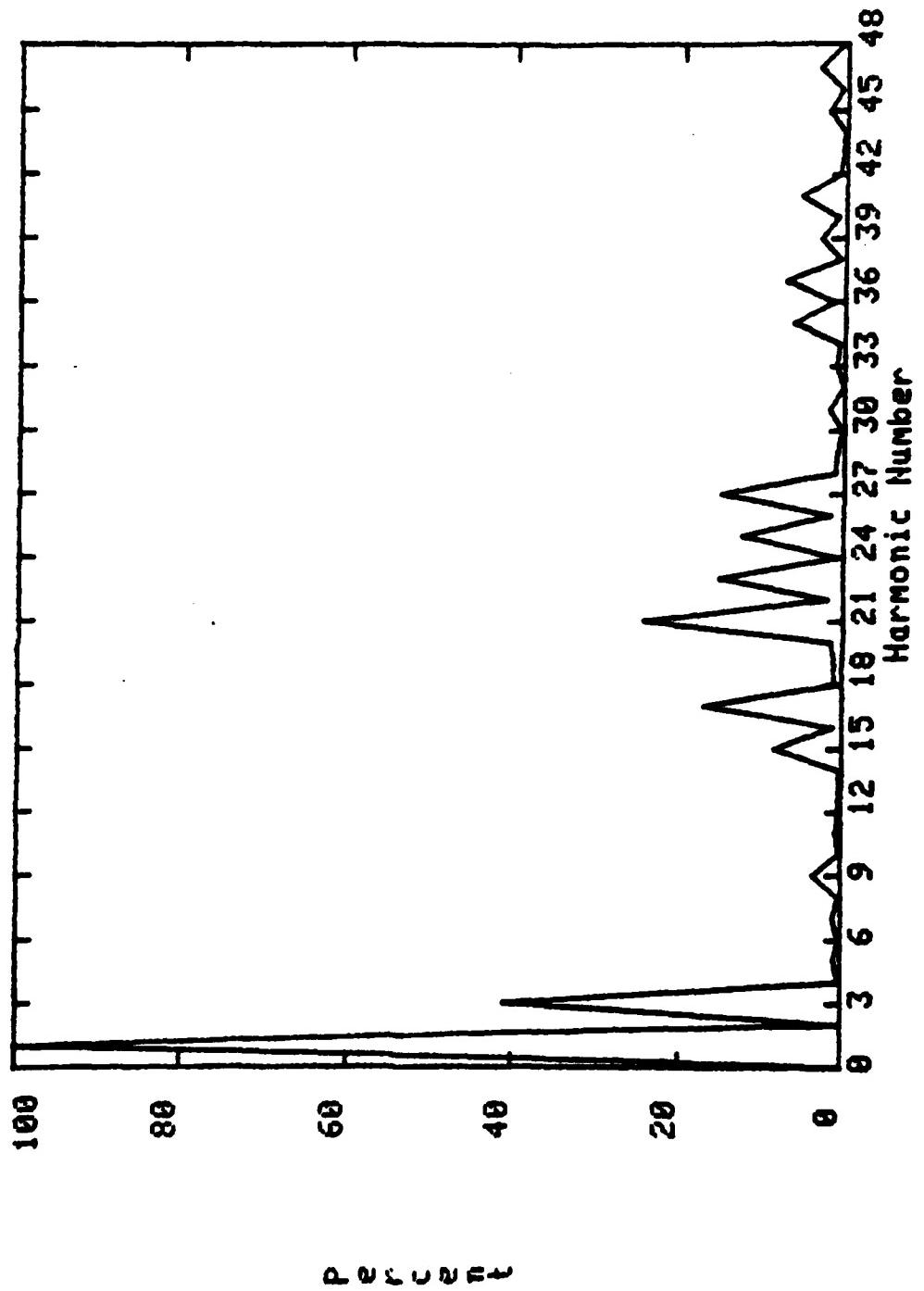


Figure 38. Fourier Spectrum of Phase Current - 2250 RPM,  $\alpha = 40^\circ$ , Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

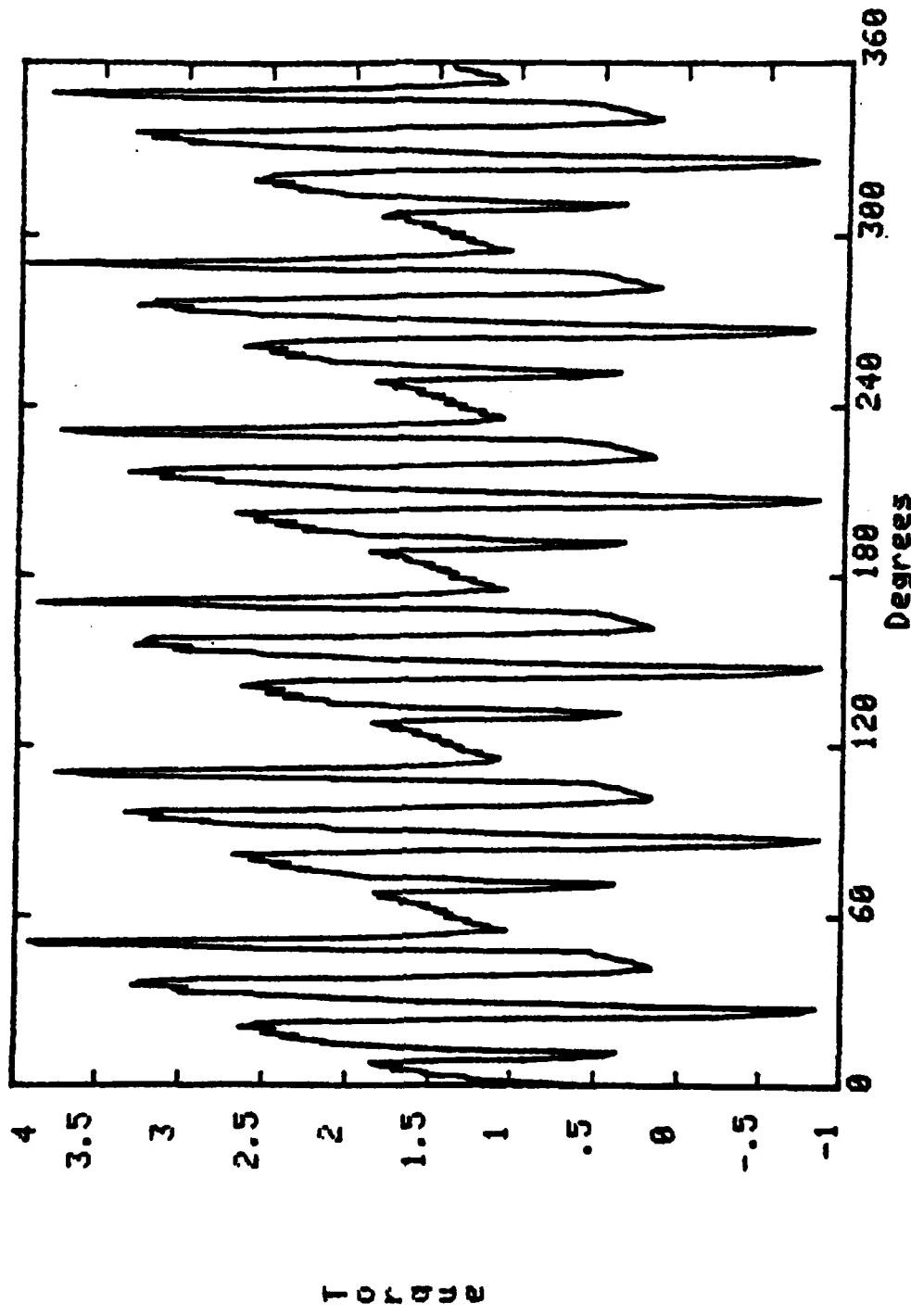


Figure 39. Developed Torque - 2250 RPM,  $\alpha = 40^\circ$ , Sixth and Twelfth Harmonics Eliminated

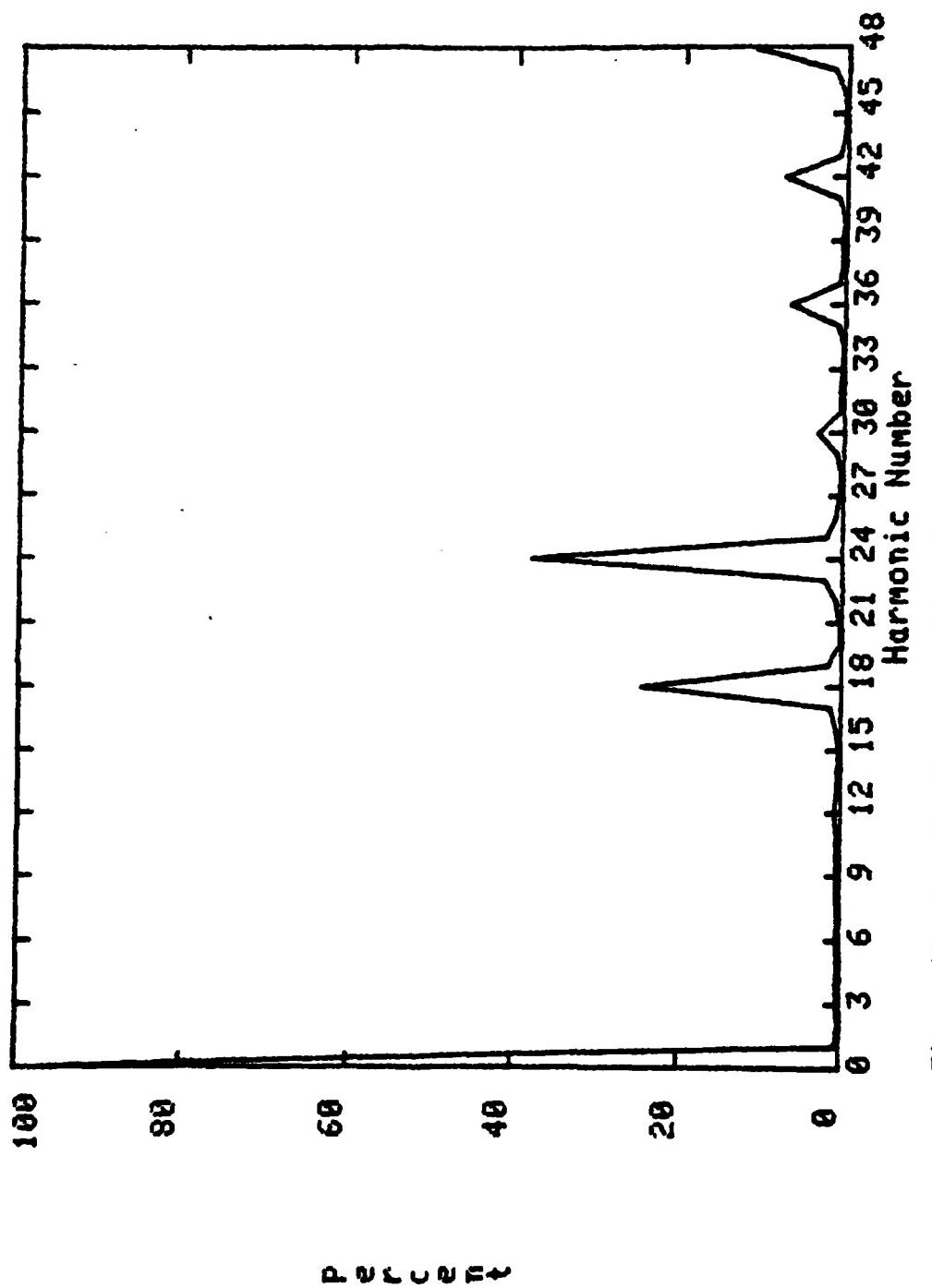


Figure 40. Fourier Spectrum of Developed Torque - 2250 RPM,  $\alpha = 40^\circ$ ,  
Sixth and Twelfth Harmonics Eliminated

### 2.3 450 RPM (1% Speed Case)

#### 2.3.1 Unmodulated Phase Voltage.

##### Input Data

Motor speed,  $n_m$  = 450 rpm  
Motor frequency,  $f$  = 15 Hz  
SCR firing angle,  $\alpha_s$  =  $64.52^\circ$   
Specified average torque,  $T_{dav}$  = 1.5 N·m

##### Output Data

Average torque,  $T_{day}$  = 1.4996 N·m  
RMS phase current,  $I_{RMS}$  = 67.1 A

A plot of phase current  $i_1$  is given by Figure 41. The associated Fourier spectrum is shown by Figure 42.

A plot of instantaneous developed torque is given by Figure 43. A Fourier spectrum of developed torque is shown by Figure 44.

The instantaneous wave form plots for the low speed case do not display all of the ripples due to the lack of capacity of the plot routine to store sufficient points.

2.3.2 Elimination of Sixth Harmonic of Torque. The sixth harmonic of torque is eliminated by removing the fifth and seventh harmonics of phase current.

##### Input Data

Motor speed,  $n_m$  = 450 rpm  
Motor frequency,  $f$  = 15 Hz  
SCR firing angle,  $\alpha_s$  =  $52.53^\circ$   
Specified average torque,  $T_{dav}$  = 1.5 N·m  
Angles of modulation function,  $\alpha_1$  =  $40.76^\circ$   
 $\alpha_2$  =  $47.73^\circ$   
 $\alpha_3$  =  $58.65^\circ$

##### Output Data

Average torque,  $T_{day}$  = 1.4996 N·m  
RMS phase current,  $I_{RMS}$  = 75.2 A

A plot of phase current  $i_1$  is given by Figure 45. The associated Fourier spectrum is shown by Figure 46.

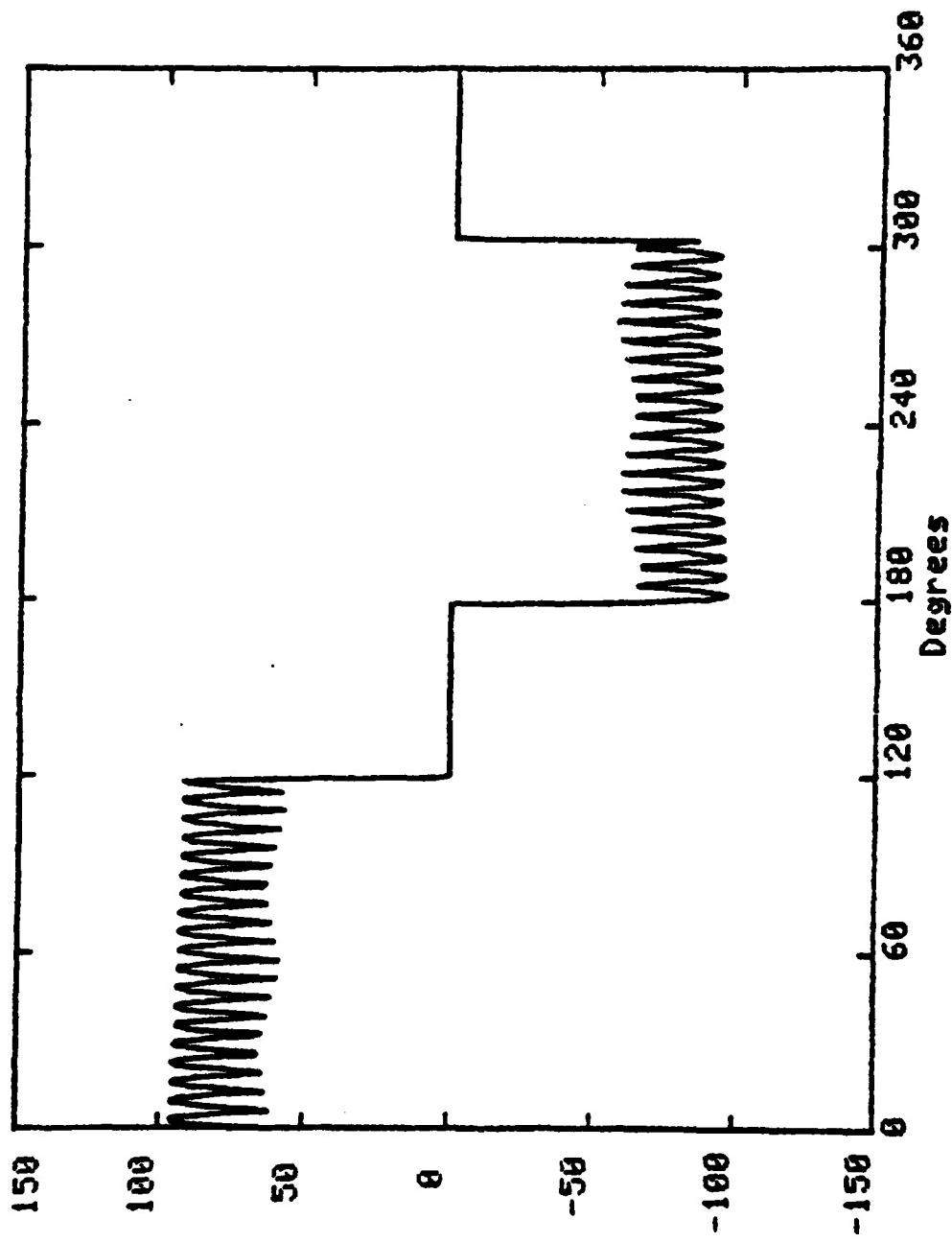


Figure 41. Phase Current - 450 RPM, No Modulation

11

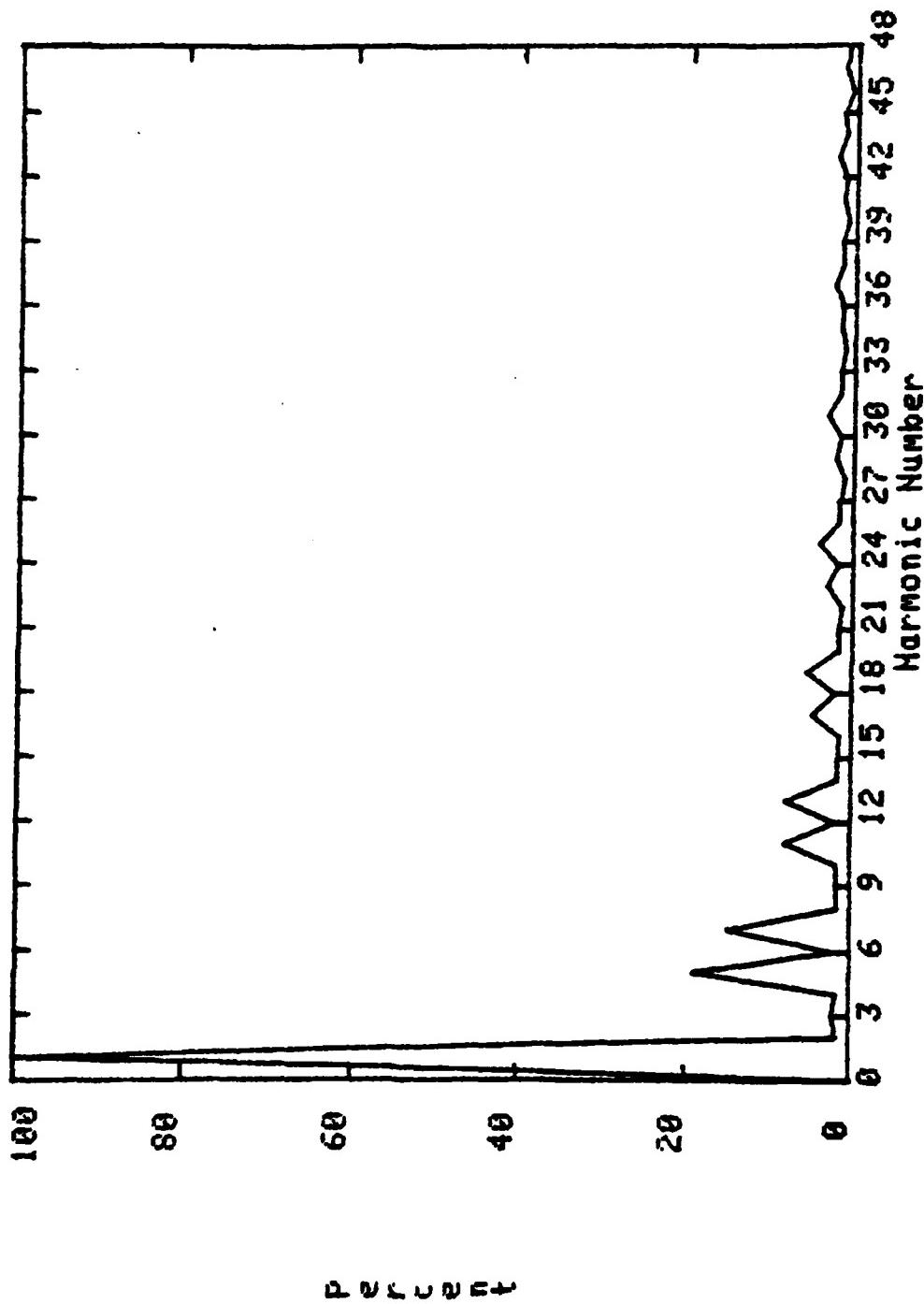


Figure 42. Fourier Spectrum of Phase Current - 450 RPM, No Modulation

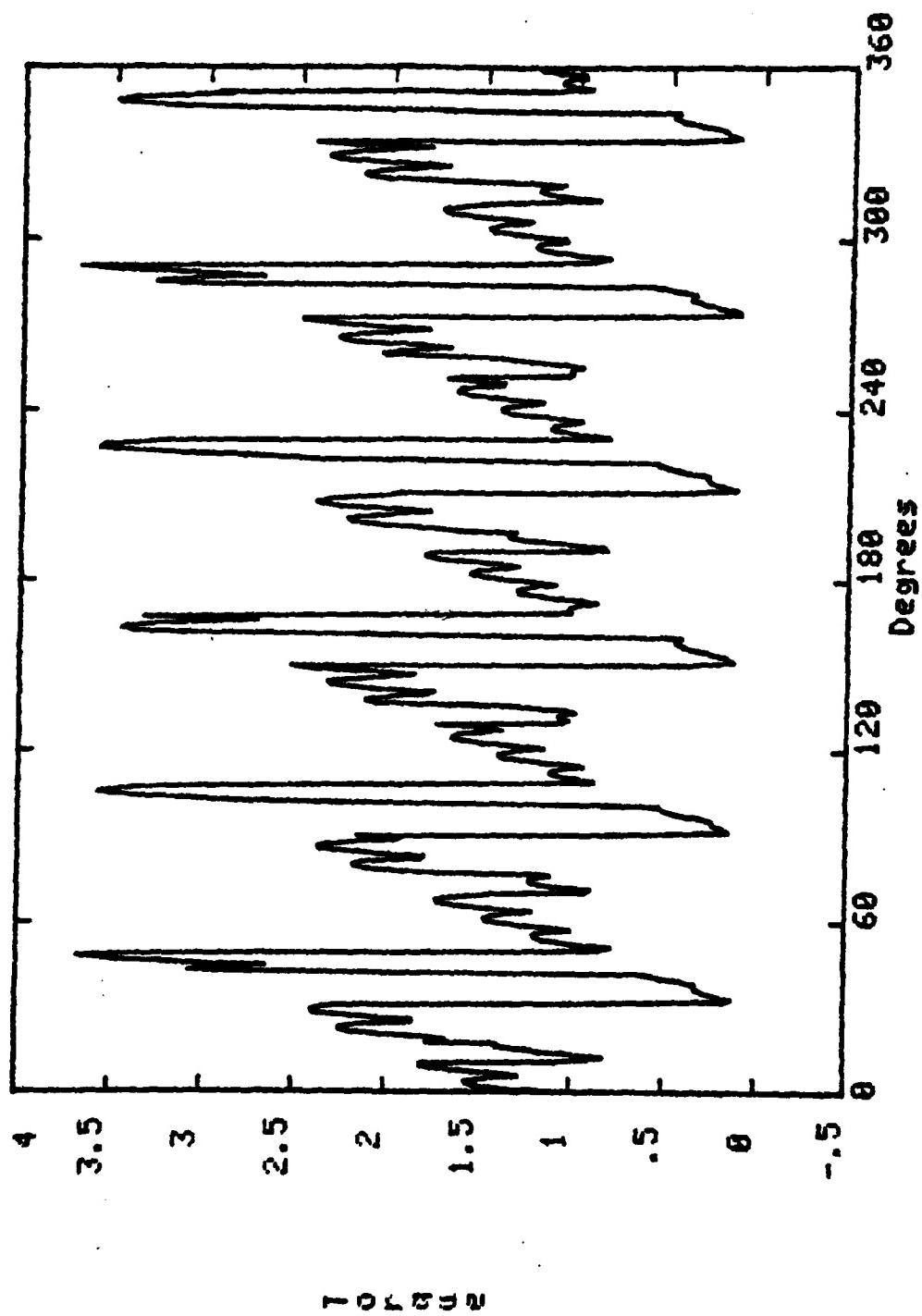


Figure 43. Developed Torque - 450 RPM, No Modulation

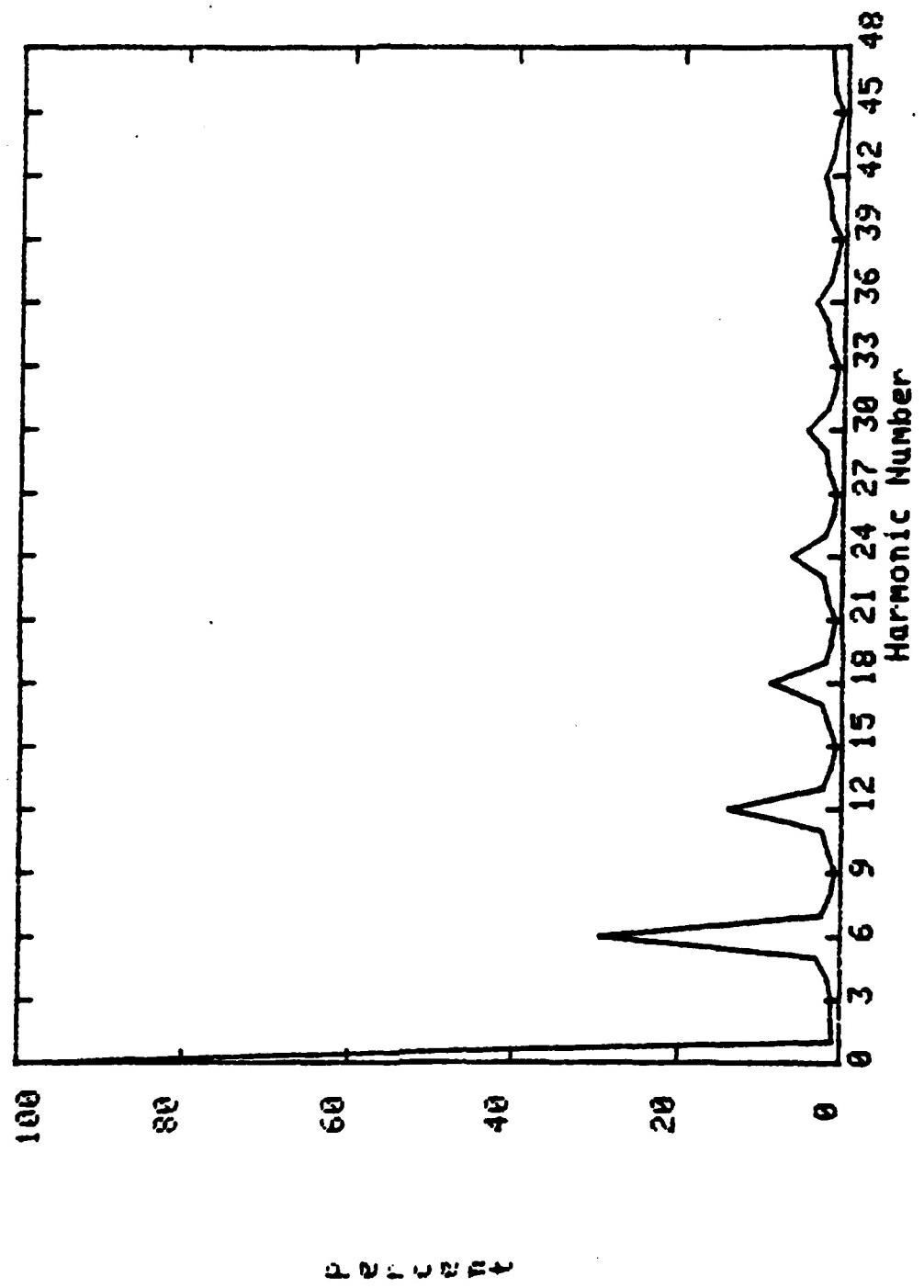


Figure 44. Fourier Spectrum of Developed Torque - 450 RPM, No Modulation

A plot of instantaneous developed torque is given by Figure 47. The Fourier spectrum of developed torque is shown by Figure 48.

2.3.3 Elimination of Sixth and Twelfth Harmonics of Torque. Both the sixth and twelfth harmonics of torque are eliminated by removing the fifth, seventh, eleventh, and thirteenth harmonics of phase current.

Input Data

Motor speed,  $n_m$  = 450 rpm

Motor frequency,  $f$  = 15 Hz

SCR firing angle,  $\alpha_s$  = 49.78°

Specified average torque,  $T_{dav}$  = 1.5 N·m

Angles of modulation function,  $\alpha_1$  = 38.73°

$\alpha_2$  = 42.13°

$\alpha_3$  = 52.25°

$\alpha_4$  = 61.93°

$\alpha_5$  = 66.86°

Output Data

Average torque,  $T_{dav}$  = 1.507 N·m

RMS phase current  $I_{RMS}$  = 77.38 A

A plot of phase current  $i_1$  is given by Figure 49. The associated Fourier spectrum of phase current is shown by Figure 50.

A plot of instantaneous developed torque is given by Figure 51. The Fourier spectrum of developed torque is shown by Figure 52.

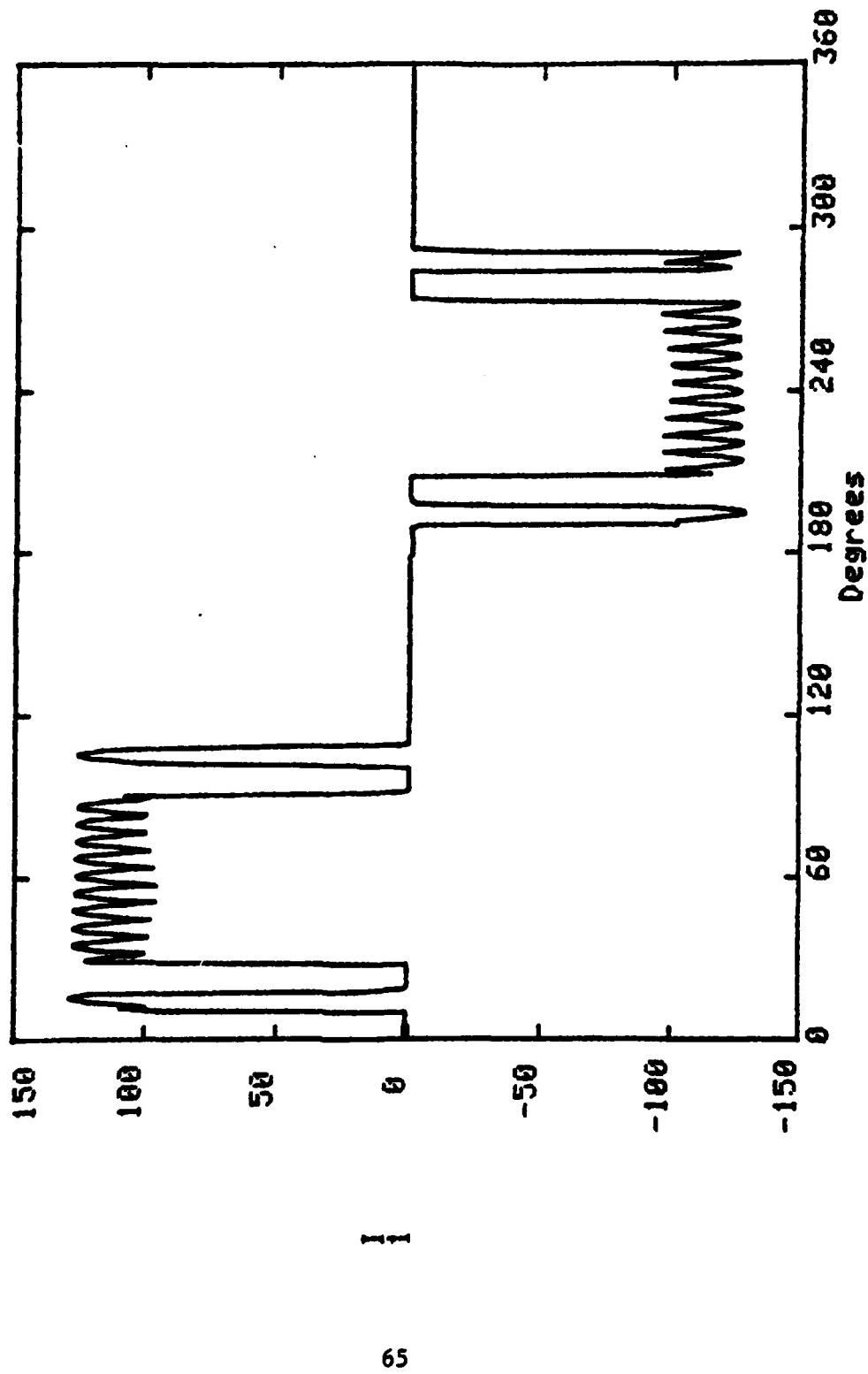


Figure 45. Phase Current - 450 RPM, Fifth and Seventh Harmonics Eliminated

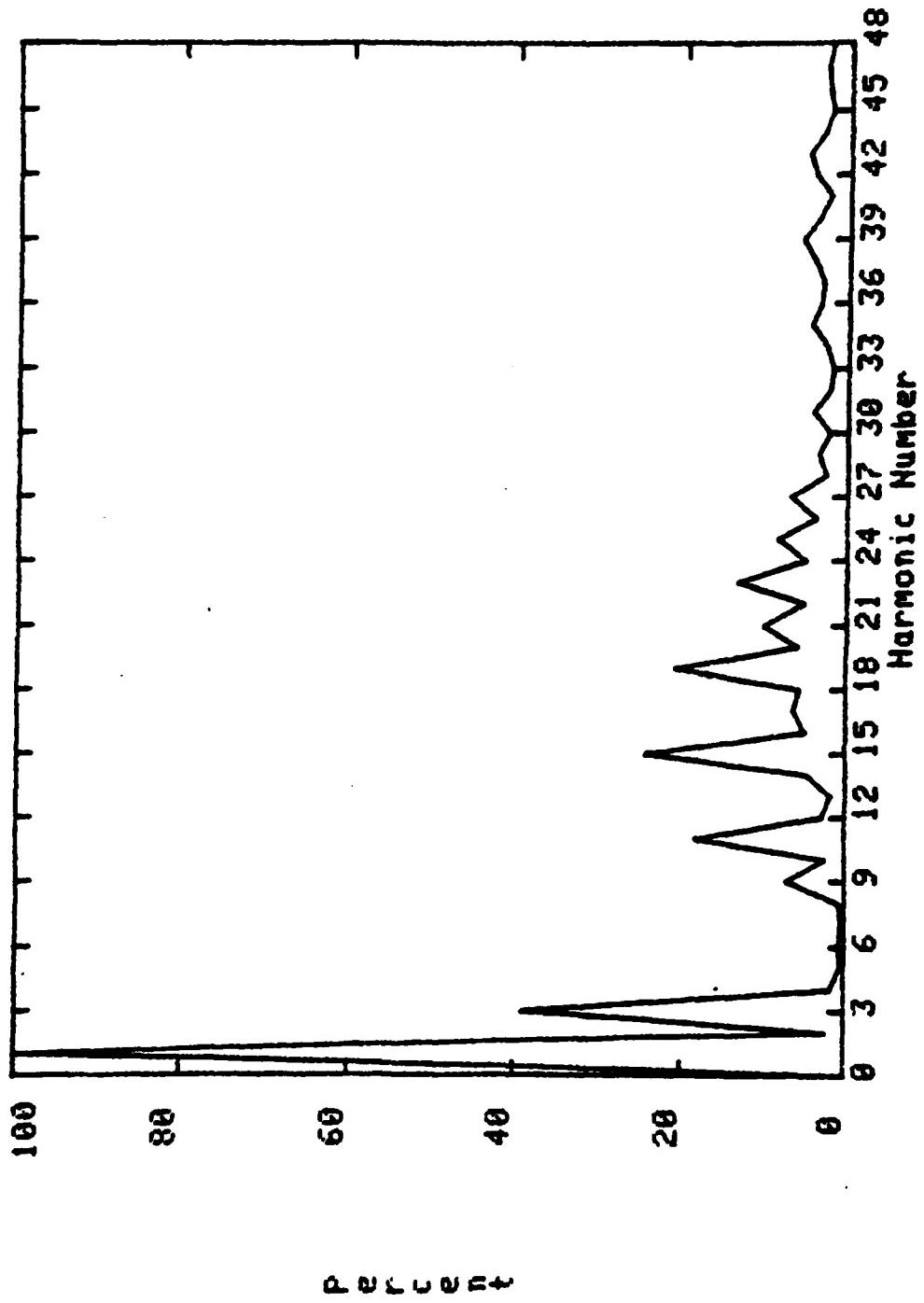


Figure 46. Fourier Spectrum of Phase Current - 450 RPM, Fifth and Seventh Harmonics Eliminated

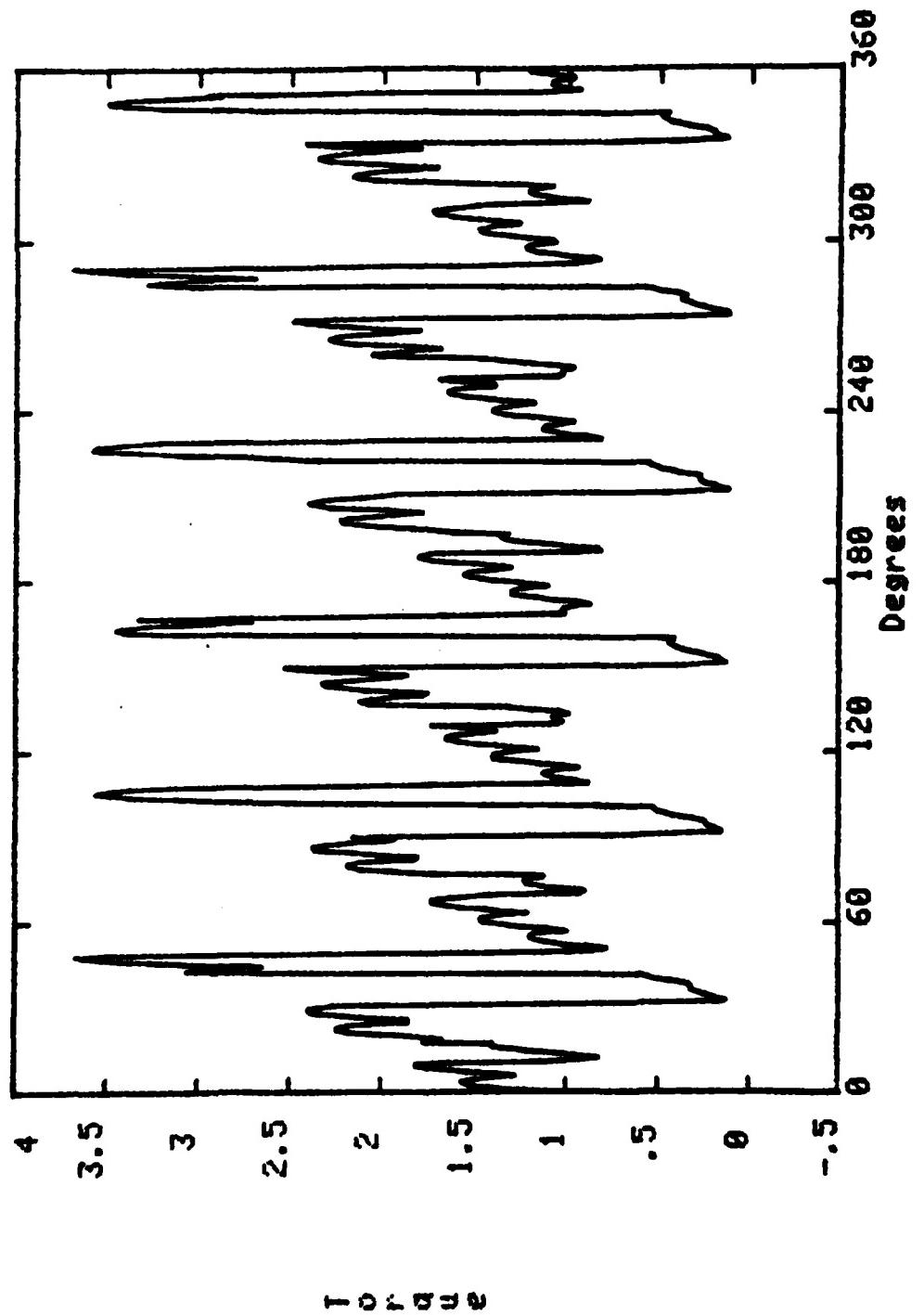


Figure 47. Developed Torque - 450 RPM, Sixth Harmonic Eliminated

TORQUE

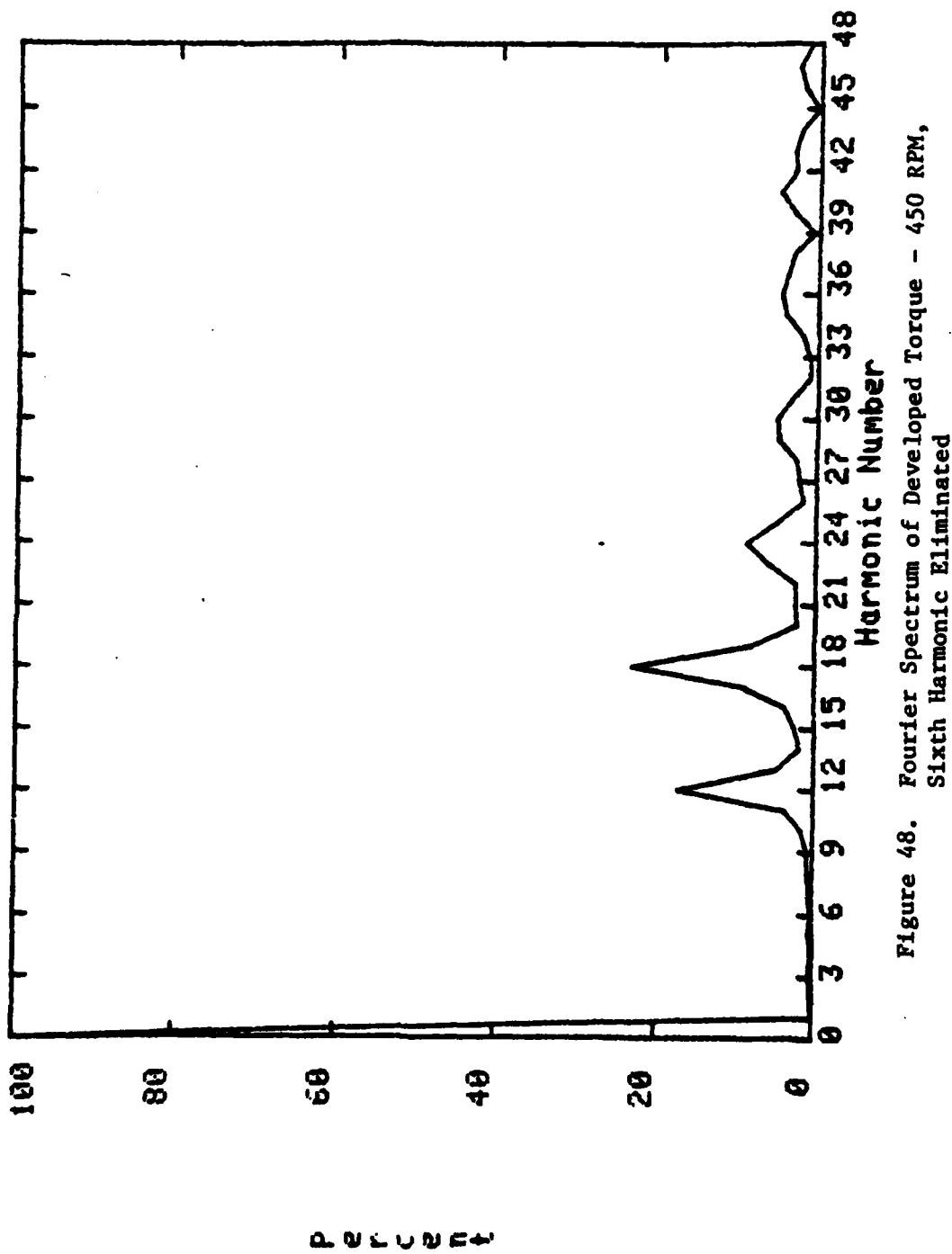


Figure 48. Fourier Spectrum of Developed Torque - 450 RPM,  
Sixth Harmonic Eliminated

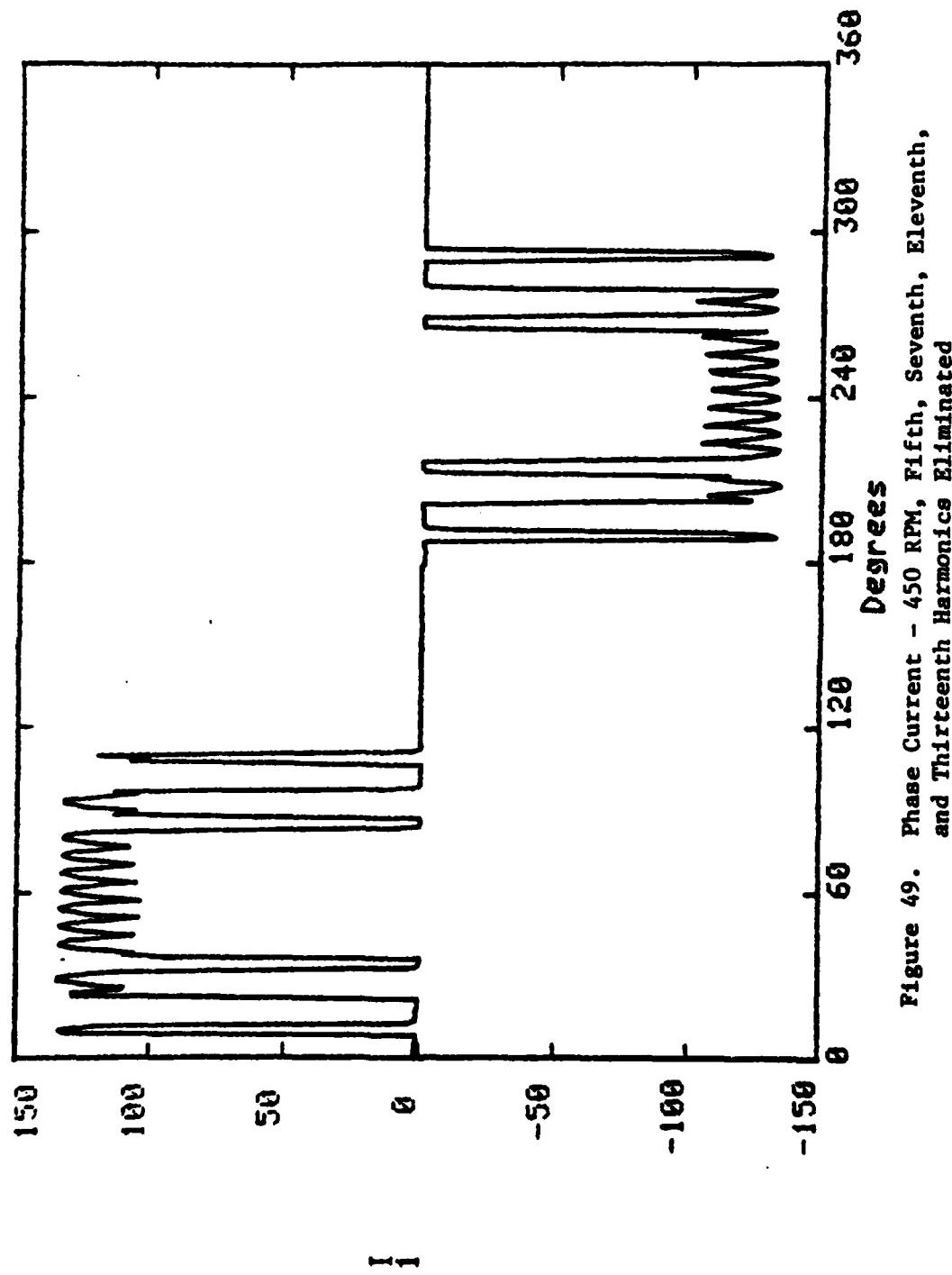


Figure 49. Phase Current - 450 RPM, Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

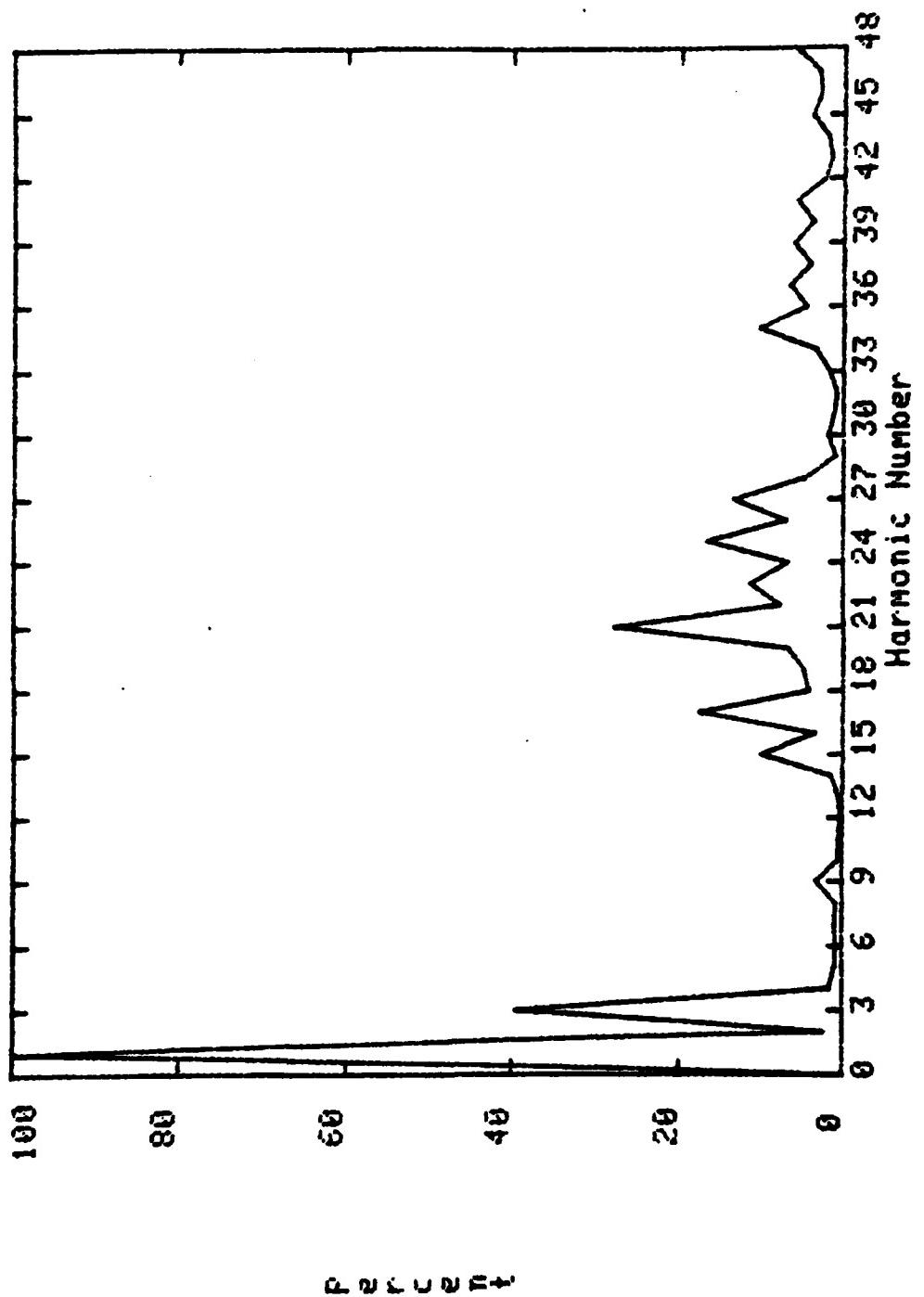


Figure 50. Fourier Spectrum of Phase Current - 450 RPM, Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

P E R C E N T

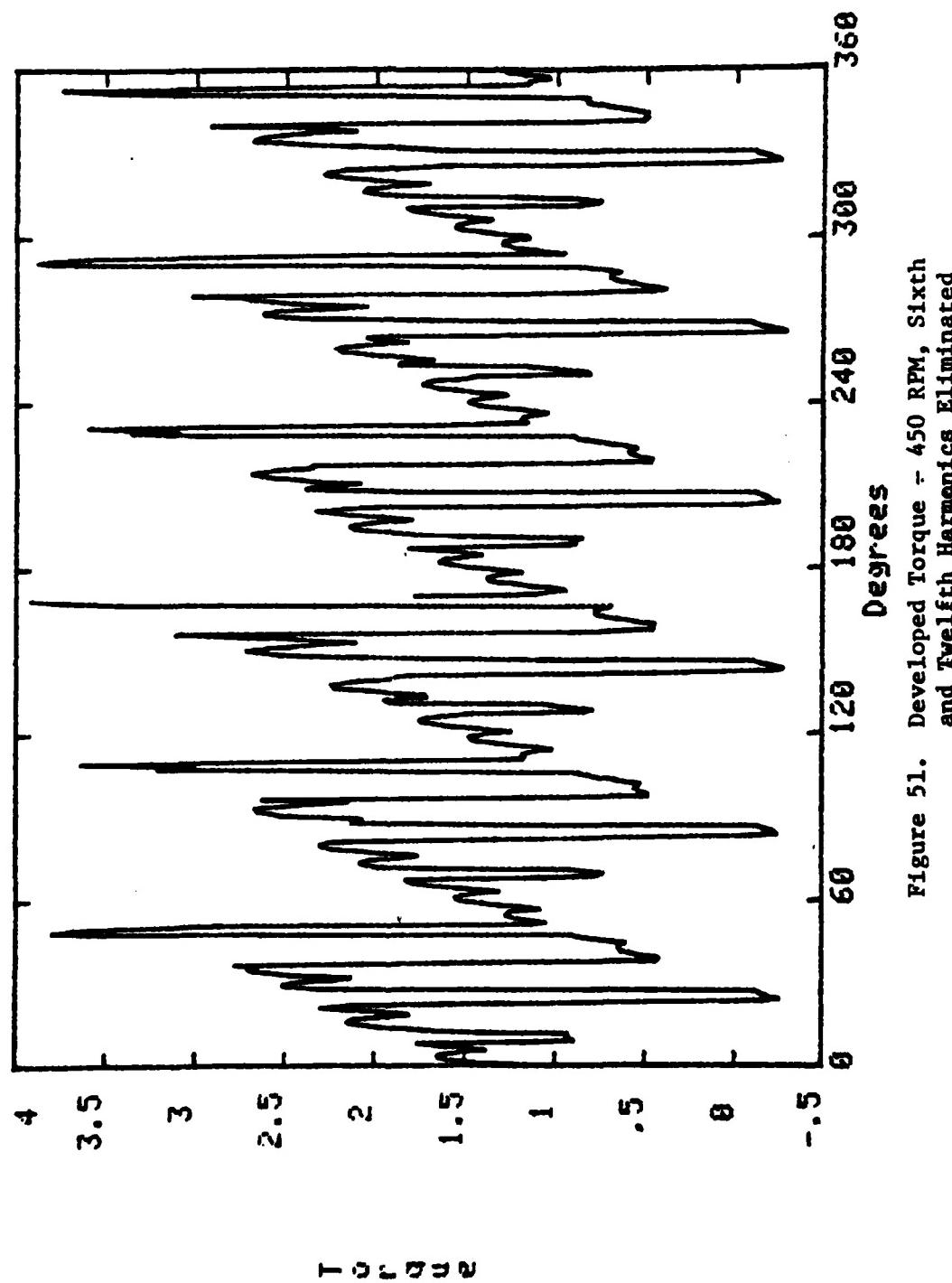


Figure 51. Developed Torque = 450 RPM, Sixth and Twelfth Harmonics Eliminated

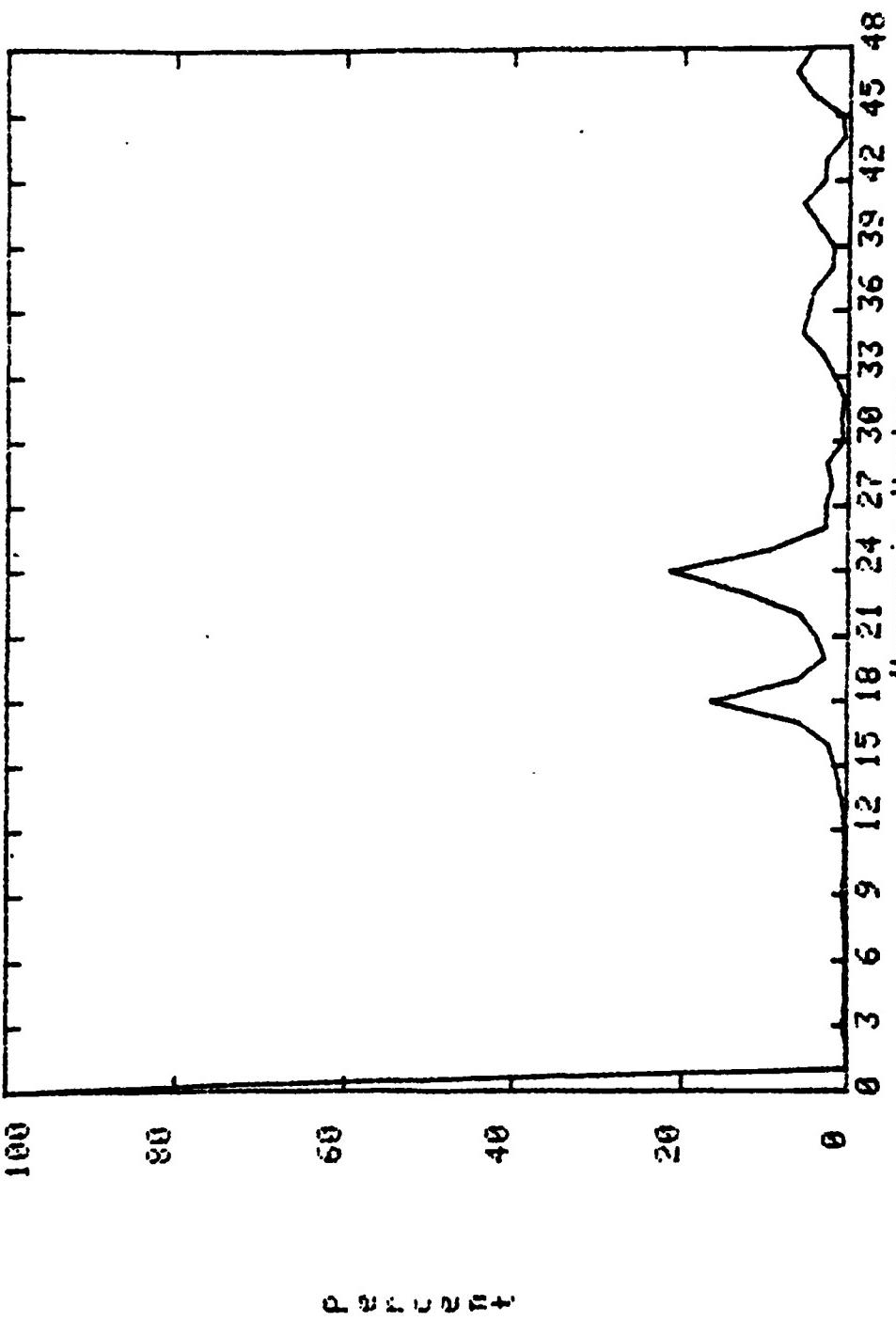


Figure 52. Fourier Spectrum of Developed Torque - 450 RPM,  
Sixth and Twelfth Harmonics Eliminated

## SECTION IV

### DISCUSSION

#### 1.0 INCREASE IN OHMIC LOSSES

Since modulation of the wave form definitely redistributes the harmonic content of the phase current wave form, an examination of the change in winding ohmic losses is in order. For the 4500 rpm case it is noted that the RMS phase current is found to be as follows:

- (a).  $I_{RMS} = 72.77 \text{ A}$  for no modulation
- (b).  $I_{RMS} = 74.24 \text{ A}$  for fifth and seventh harmonic eliminated
- (c).  $I_{RMS} = 74.59 \text{ A}$  for fifth, seventh, eleventh, and thirteenth harmonic eliminated

The increase in ohmic losses assuming a constant winding resistance is given by the ratio of RMS current for a changed condition to the RMS value of current for the unmodulated wave form. It is concluded that the ohmic losses are increased by 2.1% for the case of elimination of fifth and seventh harmonics. The ohmic losses are increased by 2.5% for the case of elimination of the fifth, seventh, eleventh, and thirteenth harmonics.

Calculated data for the 2250 rpm and 450 rpm cases show increases of 7 to 15%; however, there is no theoretical basis for greater increase in these cases. The reason for this apparent larger increase for the lower speed cases is a numerical problem due to storing and calculating the RMS value based on a limited number of data points (2000) for transmittal to the plot routine. As a result, the high frequency ripple currents are sampled at irregular intervals giving rise to inaccuracy in calculation of the RMS value. For the case of 4500 rpm, the data point limit allows storage of several points during each ripple cycle, thus, the resulting RMS values are considerably more accurate than for the other two speed cases.

#### 2.0 CYCLOCONVERTER MODE CHANGE

As discussed and illustrated by Figure 2, a neutral connection is necessary to successfully eliminate selected phase current harmonics. Since harmonic elimination is only necessary at speeds near zero, and since an ohmic loss penalty is incurred as a result, it might be desirable to not operate with PWM control over the full range of speed. The Harmonic Eliminator Switch in the neutral line of Figure 2 could be opened for higher speeds and the cycloconverter mode of operation changed to phase-control from synchronous envelope.

### **3.0 EXTENSION TO HIGHER HARMONIC ELIMINATION**

For specific illustration, this study has only considered elimination of torque harmonics through the twelfth. As motor speed approaches zero, it may be necessary to eliminate even higher torque harmonics. Theoretically, there is no limitation to be encountered.

SECTION V  
CONCLUSIONS AND RECOMMENDATIONS

The work performed by this study shows that systematic reduction of harmonic torque pulsations in brushless DC drives is feasible by use of selective current harmonic elimination. Further, there appears to be only a small ohmic loss penalty.

Further theoretical study should be made to properly assess quantitatively the effect of increased motor leakage inductance and of interphase reactors on "reintroducing" the harmonics eliminated from the phase voltage due to extending the commutation overlap.

Also, a hardware realization of a midpoint cycloconverter brushless DC drive using the control principles formulated in this study should be made to verify the results.

## SECTION VI

### REFERENCES

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## APPENDIX A

### HARMONICS OF PWM TIME FUNCTION

A modulation function  $h(\omega t)$  was derived in Appendix B and used in Section II - 5.0 to form a modulated phase voltage. For example,  $v_{an} = h(\omega t) v_d(t)$ .

Harmonic content of a modulated voltage is of concern. The study is best understood by use of a typical example. Let  $h(\omega t)$  contain all odd harmonics except the fifth and seventh, then

$$h(\omega t) = a_1 \cos \omega t + a_3 \cos 3\omega t + a_9 \cos 9\omega t + a_{11} \cos 11\omega t + \dots \\ + a_n \cos n\omega t + \dots \quad (A.1)$$

Assume the  $v_d(t)$  contains a DC term plus one high frequency harmonic, then

$$v_d(t) = b_0 + b_m \cos m\omega t \quad (A.2)$$

Forming  $v_{an}$  as the product of  $h(\omega t)$  and  $v_d(t)$  and simplifying yields

$$v_d(t) = c_1 \cos \omega t + c_3 \cos 3\omega t + c_9 \cos 9\omega t + c_{11} \cos 11\omega t + \dots \\ + d_{m+1} \cos(m+1)\omega t + d_{m-1} \cos(m-1)\omega t + d_{m+3} \cos(m+3)\omega t \\ + d_{m-3} \cos(m-3)\omega t + \dots \quad (A.3)$$

It is seen from (A.3) that through the cross product terms, the PWM expression may contain frequencies that were selectively eliminated from  $h(\omega t)$ . However, the coefficients ( $d_{m+1}, d_{m-1}, \dots$ ) of (A.3) are products of  $a_n$  and  $b_m$ . Since  $a_n$  decreases as  $1/n$ , if  $m$  is large, then the coefficients of the low frequency components of  $h(\omega t)$  resulting cross product terms will be negligibly small. It is concluded that the frequency of the AC source must be large compared with the motor frequency if the PWM function is to not contain the harmonics selectively eliminated from the modulating function  $h(\omega t)$ . But, at near zero speed, the source frequency is large compared with the motor frequency.

APPENDIX B  
MODULATION FUNCTION PROGRAMS

### 1.0 INITIAL SOLUTION

As first procedure, a candidate or initial modulation function,  $h(\omega t)$ , is found to serve as a basis for an optimization search to determine the final modulation function.

#### 1.1 Theory of Harmonic Elimination

Extending Patel and Hoft's pulse width modulation technique [14] to include a slack variable, it is possible to find a modulation function that has selected harmonics elimination while existing on the quarter wave interval from  $30^\circ$  to  $90^\circ$ .

The Fourier series representation of the modulation function assuming odd quarter wave symmetry is

$$f(\omega t) = \sum_{n=1}^{\infty} a_n \sin(n\omega t), \quad \text{for odd } n$$

where

$$a_n = \int_{\alpha_1}^{\alpha_2} \sin(n\omega t) d\omega t + \int_{\alpha_3}^{\alpha_4} \sin(n\omega t) d\omega t + \cdots + \int_{\alpha_{M-1}}^{\alpha_M} \sin(n\omega t) d\omega t, \quad (B.1)$$

$$30^\circ < \alpha_1 < \alpha_2 < \cdots < \alpha_M < 90^\circ$$

This reduces to

$$a_n = \frac{4}{n\pi} \sum_{k=1}^M (-1)^{k+1} \cos(n\alpha_k) \quad (B.2)$$

for M both odd and even. The number of harmonics eliminated is in general the same as the number of switching transitions per quarter cycle. For M greater than 2 the equations cannot be solved in closed form, so numerical methods are needed to obtain solutions. The following normalized system of equations is to be used to obtain solutions:

$$\begin{aligned} f_{n1} &= \sum_{k=1}^M (-1)^{k+1} \cos(n_1 \alpha_k) = 0 \\ f_{n2} &= \sum_{k=1}^M (-1)^{k+1} \cos(n_2 \alpha_k) = 0 \\ &\vdots \\ f_{nM} &= \sum_{k=1}^M (-1)^{k+1} \cos(n_M \alpha_k) = 0 \end{aligned} \quad (B.3)$$

where  $n_1, n_2, \dots, n_M$  are the harmonics to be eliminated.

Many of the solutions of (B.3) are meaningless or impractical, so it is necessary to search by brute force using a loose convergence criterion for candidate solutions, and then to use a numerical method such as Newton-Raphson to obtain a refined solution.

The basic method of selecting candidate modulation function for further optimization is illustrated by the flow chart of Figure B.1. A candidate set is one that meets the following criteria:

$$f_{\text{square}} < f_{\text{min}}$$

$$f_{\text{square}} = f_{n1}^2 + f_{n2}^2 + \dots + f_{nM}^2$$

If for the candidate modulation function,  $30^\circ < a_1 < a_2 < \dots < a_M < 90^\circ$ , then the solution is considered for optimization. Otherwise, the solution is discarded.

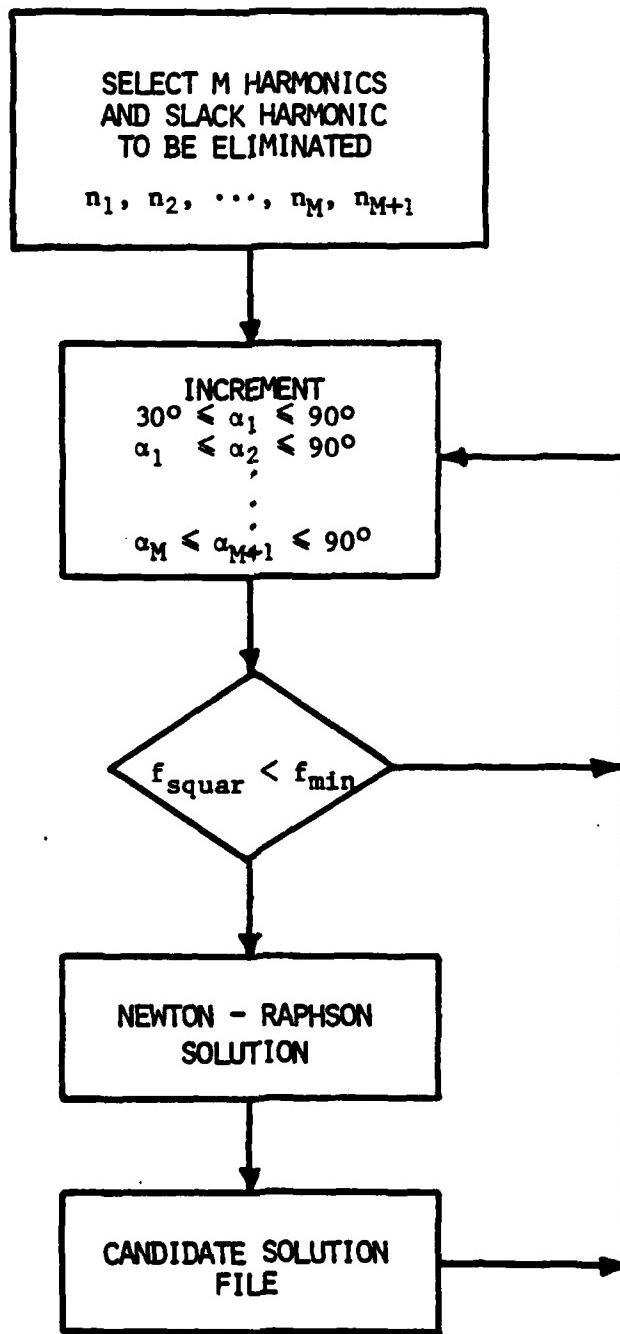


Figure B.1. Flow Chart for Selection of Candidate Modulation Functions

## 1.2 Initial Solution Program



```
if( k2 .lt. k2max .and. n .ge. 2 ) go to 205
if( k1 .lt. k1max .and. n .ge. 1 ) go to 105
write(6,3100)
write(6,3000) ( a(i)*conv,i=1,n )
call sclose(0.0)
3000  format( 10(e15.7,5x) )
3100  format(' a=')
3200  format(' harmonics=')
      stop
      end
```









```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                                     c
c          subroutine look           c
c                                     c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
    subroutine look( a,r,f,fsquare,n )
dimension da(10),r(10),a(10),f(10),df(10,10),dfi(10,10)
common pi,conv,iwr,del
write(6,3050)
write(6,3050)
write(6,3100)
write(6,3000) ( a(i)*conv,i=1,n )
write(6,3150)
write(6,3000) ( f(i),i=1,n )
write(6,3200)
write(6,3000) fsquare
kount=30
fmin=0.01
delta=0.001

do 2500 loop=1,kount
call fdf( a,r,f,df,n )
call matv( df,n,det,dfi )
call mult1( f,dfi,da,n,n )
call fa( a,da,n )
call ff( a,r,f,n )
call square( f,fsquare,n )
if( loop .gt. 5 .and. fsquare .lt. fmin ) go to 2900
2500 continue
2900 write(6,3050)
write(6,3100)
write(6,3000) ( a(i)*conv,i=1,n )
write(6,3150)
write(6,3000) ( f(i),i=1,n )
write(6,3200)
write(6,3000) fsquare
3000 format( 10(e10.4,5x) )
3050 format( ' ' )
3100 format( ' a=' )
3150 format( ' f=' )
3200 format( ' fsquare=' )
4000 format('test',13)
5000 return
end

```

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HARMONIC CONTROL TO REDUCE TORQUE PULSATIONS IN  
BRUSHLESS DC MOTOR DRIVES(U) KENTUCKY UNIV RESEARCH  
FOUNDATION LEXINGTON J J CATHEY MAR 84

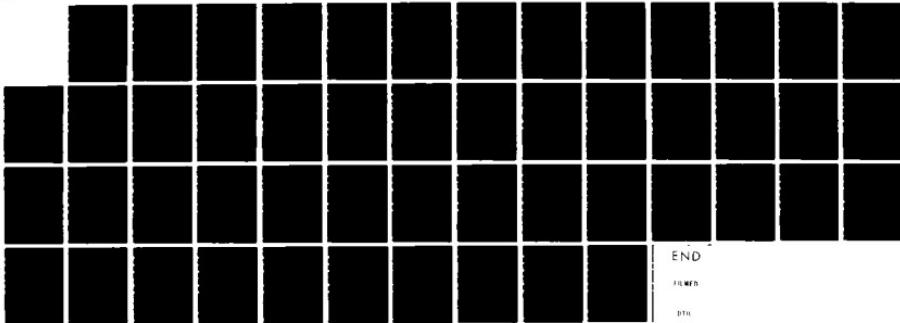
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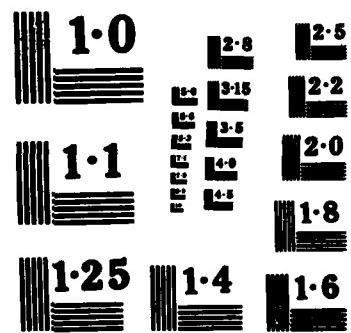
NL



END

110000

0TH







```
DO 95 I=1,N
L=N-I+1
IF(INDEX(L,1)-INDEX(L,2) ) 85,95,85
85      JROW=INDEX(L,1)
      JCOL=INDEX(L,2)
      DO 90 K=1,N
            T=B(K,JROW)
            B(K,JROW)=B(K,JCOL)
            B(K,JCOL)=T
90      CONTINUE
95      CONTINUE
100     RETURN
      END
```







## 2.0 OPTIMIZATION OF MODULATION FUNCTION

### 2.1 Discussion of Procedure

A candidate solution for the modulation function is selected from the output of the Initial Solution Program for optimization. The slack harmonic of the initial solution is changed in small increments and fed to a Newton-Raphson routine to find the new set of solutions. A continuous set of  $\alpha$ 's results from this procedure having "nice" properties. First, the new set of solutions is well behaved in that meaningless sets of solutions are not encountered and convergence is quick. Second, the procedure gives a "visual" picture of the behavior of the solutions in relation to the slack variable.

Since infinite number of modulation functions exist, some method is needed to select the "best" solution. The criteria used in this study was minimizing the sum of the squares of the magnitudes of the next set of current harmonics to be eliminated beyond those of present concern. For example, if the fifth and seventh harmonics were being eliminated from  $h(t)$ , then the procedure is to minimize the sum of the square of the magnitudes of the eleventh and thirteenth harmonics.

A flow chart illustrating optimization of the modulation function is given by Figure B.2.

Figure B.3 illustrates the form of the modulation function for the case of elimination of fifth and seventh harmonics and for the case of elimination of fifth, seventh, eleventh, and thirteenth harmonics.

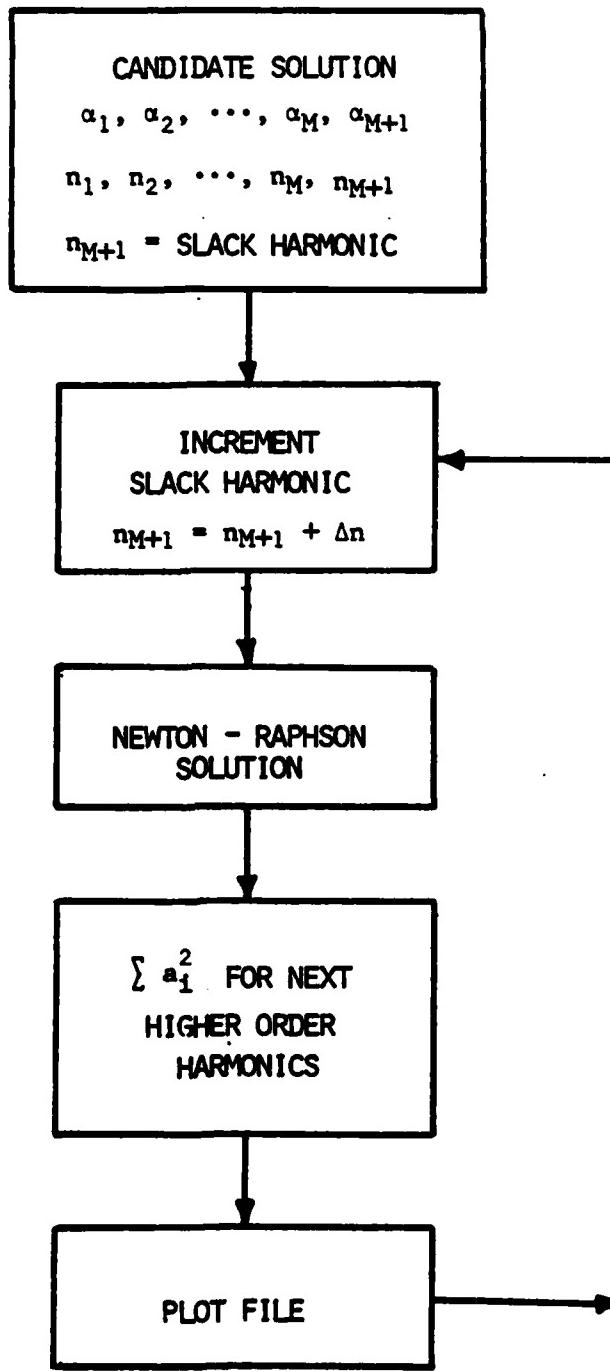
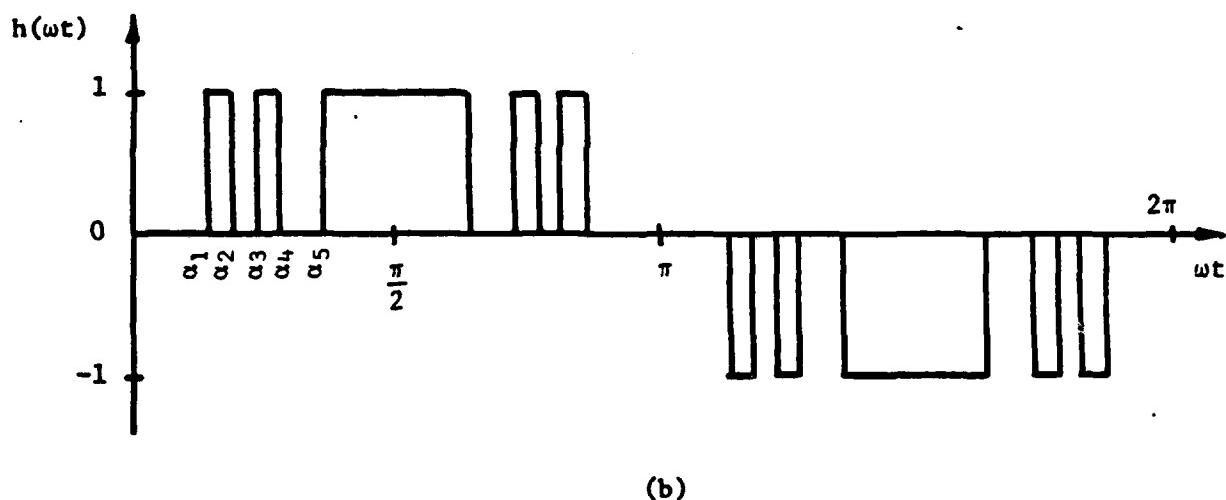
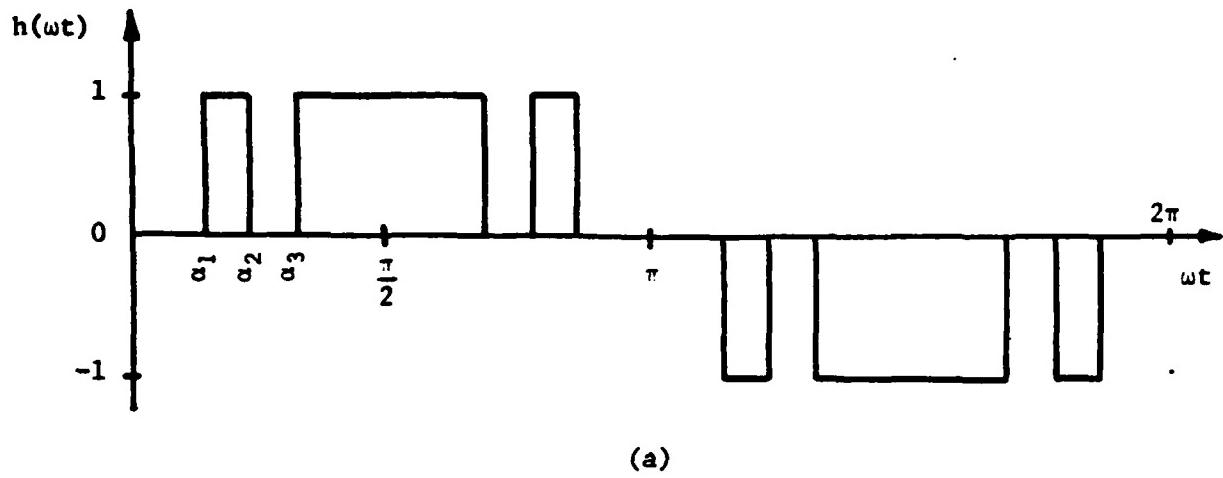


Figure B.2. Flow Chart for Optimizing Modulation Function



**Figure B.3.** Form of Modulation Functions.

- (a) Fifth and Seventh Harmonics Eliminated
- (b) Fifth, Seventh, Eleventh, and Thirteenth Harmonics Eliminated

## 2.2 Modulation Function Optimization Program

```

      do 50 i=1,5
         a(i)=a(i)/conv
50   continue
      do 100 ir=minr,maxr
         if( incre .eq. 1 ) r(n+1)=float(ir)*rinc
         if( incre .eq. 0 ) r(n+1)=float( maxr+minr-ir )*rinc
         call ff( a,r,f,n+1 )
         call square( f,fsquar,n+1 )
         call look( a,r,f,fsquar,n+1 )
         call shar( a,tr,h,n+1,msq+1 )
         call shsq( h,hsquar,msq )
         hmag=sqrt( hsquar )
         write(1,*) ( a(i)*conv,i=1,n+1)
         write(2,1000) h(1)
         write(3,1000) h(2)
         write(4,1000) h(3)
         write(7,1000) r(n+1)
         write(8,1000) hmag
100  continue
         call sclose(0.0)
1000 format( e10.4 )
3000 format( 10(e15.7,5x) )
3100 format(' a=')
3200 format(' harmonics=')
         stop
         end

```



















```
DO 95 I=1,N
L=N-I+1
IF(INDEX(L,1)-INDEX(L,2) ) 85,95,85
85    JROW=INDEX(L,1)
      JCOL=INDEX(L,2)
      DO 90 K=1,N
          T=B(K,JROW)
          B(K,JROW)=B(K,JCOL)
          B(K,JCOL)=T
90    CONTINUE
95    CONTINUE
100   RETURN
     END
```









## APPENDIX C

## FOURIER SPECTRUM PROGRAM

```
200 continue

write(6,") "avemag=",avemag
write(6,") "rms=",sqrt( rms#2.0 )
write(6,") "rms normalized=",sqrt( rms/2.0 )/avemag

2000 format( e10.4 )
call sclose(0.0)
stop
end
```



```

c
c
c
c**The following fft subroutine is taken almost verbatim
c**from Ahmed N., Rao K.R., Orthogonal Transforms for
c**Digital Signal Processing, Springer-Verlag, 1975., pp79
c
c
c
c subroutine fft(x,n,inv)
c*****cccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c this program implements the fft algorithm to compute the discrete
c fourier coefficients of a data sequence of n points
c
c calling sequence from the main program:
c call fft(x,n,inv)
c      n: number of data points
c      x: complex array containing the data sequence. In the end dft
c          coeffs. are returned in the array. Main program should
c          declare it as-- complex x(1024)
c      inv: flag for inverse
c          inv=0 for forward transform
c          inv=1 for inverse transform
c
c*****cccccccccccccccccccccccccccccccccccccccccccccccccccc
c      complex x(1030),w,t,cmplx
c
c      calculate the # of iterations (log. n to the base 2)
c
c      iter=0
c      irem=n
c      10 irem=irem/2
c      if (irem.eq.0) go to 20
c      iter=iter+1
c      go to 10
c      20 continue
c      sign=-1
c      if (inv.eq.1) sign=1
c      nxp2=n
c      do 50 it=1,iter
c
c      computation for each iteration
c      nxp:number of points in a partition
c      nxp2:nxp/2
c      nxp=nxp2
c      nxp2=nxp/2
c      wpwr=3.141592/float(nxp2)
c      do 40 m=1,nxp2
c

```

```

c      calculate the multipier
c
c      arg=float(m-1)*wpwr
w=cmplx(cos(arg),sign*sin(arg))
do 40 mxp=nxp,n,nxp
c
c      computation for each partition
c
j1=mxp-nxp+m
j2=j1+nxp2
t=x(j1)-x(j2)
x(j1)=x(j1)+x(j2)
40 x(j2)=t*w
50 continue
c
c      unscramble the bit reversed dft coeffs.
c
n2=n/2
n1=n-1
j=1
do 65 i=1,n1
if(i.ge.j) go to 55
t=x(j)
x(j)=x(i)
x(i)=t
55 k=n2
60 if(k.ge.j) go to 65
j=j-k
k=k/2
go to 60
65 j=j+k
if (inv.eq.1) go to 75
do 70 i=1,n
70 x(i)=x(i)/float(n)
75 continue
return
end

```



## APPENDIX D

## PERFORMANCE PROGRAM



```

        if( imodon .eq. 0 ) a(j)=pi/2.0
        if( imodon .eq. 0 ) a(1)=30.00*pi/180.0
4      continue
        m=3
        pfw=(rpm0/45000.0)**2*330.0
        wm=rpm0*pi/30.0
        if( iwg0n .eq. 1 ) wg=7950*pi
        if( iwg0n .eq. 0 ) wg=xwg*wm
        wm=abs(wm)
        p=4.0
        t=0.0
        w=p/2.0*wm
        ws=2.0*wg
        vm=sqrt(3.0)*xkg*wg
        write(6,*)
        ' vm=',vm
        alpha=alpha*conv
        area=0.5+0.5*( pi/3.0-a(1)+a(2)-a(3)+a(4)-a(5) )/( pi/3.0 )
        if( imodon .ne. 0 .and. iarea .eq. 1 ) vdc=vdc/area
        if( ifull .eq. 1 ) alphs(1)=acos( (vdc*sqrt(2.0))/(1.0*vm*1.35) )
        if( ifull .eq. 1 ) alphs(2)=acos( (vdc*sqrt(2.0))/(2.0*vm*1.35) )
        if( ifull .eq. 0 ) alphs(1)=acos( (vdc*sqrt(2.0))/(0.5*vm*1.35) )
        if( ifull .eq. 0 ) alphs(2)=acos( (vdc*sqrt(2.0))/(1.0*vm*1.35) )
        write(6,*)
        ' alphs(1)=' ,alphs(1)/conv
        write(6,*)
        ' alphs(2)=' ,alphs(2)/conv
        write(6,*)
        ' area=' ,area
        write(6,*)
        ' f=' ,w/(2.0*pi)
        write(6,*)
        ' fs=' ,ws/(2.0*pi)
        write(6,*)
        ' mag of e1=' ,xk*w/2.0
        xx(1)=0.0
        xx(2)=0.0
        xx(3)=0.0
        pd=0.0
        pin=0.0
        iav=0.0
        irms=0.0
        e1ave=0.0
        vdave=0.0
        e1rms=0.0
        sum=0.0
        tp=2.0*pi/w
        tmin=pmin*tp
        tmax=pmax*tp
        tmxmn=tmax-tmin
        scale=30.0/points
        k0=int( tmxmn/tp*scale/abs(rpm0)/h )
        kount=0
        index=1
        rewind(9)
        read(9,*)
        istop
        if( istop .eq. 1 ) go to 305

```

100

```

kount=kount+1
200
ang=w*t
iprin1=int(ang/2.0/pi)
ang=ang-float(iprin1)*2.0*pi
e(1)=xk*w*2.0/p*sin(ang-alpha)
e(2)=xk*w*2.0/p*sin(ang-alpha-2.0/3.0*pi)
e(3)=xk*w*2.0/p*sin(ang-alpha+2.0/3.0*pi)
wst=ws*t0
if( wst .ge. 2.0*pi ) t0=0.0
wst=ws*t0
if( ifull .eq. 0 ) call half( wst,xlamda )
if( ifull .eq. 1 ) call full( wst,xlamda )
call fv( a,ang,v,vd,alphs,xlamda )
call ff( index,t,f,x,xi,ang,del,v )
if( ichon .eq. 1 ) call check( m,x,f )
call derk( m,x,f,t,t0,h,index )
if( index .eq. 2 ) go to 200
if( t .lt. tmin ) go to 100
f(1)=( x(1)-xx(1) )/h
f(2)=( x(2)-xx(2) )/h
f(3)=( x(3)-xx(3) )/h
do 86 kk=1,3
  xx(kk)=x(kk)
86
continue
call ffi( fi,f,ang )
call fvap( wst,vap,alphas )
v1p=vd-fi*xl0/2.0-x1*r0-x(1)*(r(1)-ra)
vscr=vap-v1p
if( ang .lt. 3.0/3.0*pi .and. wst .lt. 2.0/3.0*pi )
c   vscr=x(1)*(r(1)-ra)
if( ang .ge. 3.0/3.0*pi .and. wst .ge. 3.0/3.0*pi .and.
c   wst .lt. 4.0/3.0*pi ) vscr=x(1)*(r(1)-ra)
85
if( t .ge. tmax ) go to 300
if( kount .lt. k0 ) go to 100
300
sum=sum+1.0
pd1=x(1)*e(1)
pd2=x(2)*e(2)
pd3=x(3)*e(3)
td=( pd1+pd2+pd3 )/wm
pd=pd+( pd1+pd2+pd3 )
pin=pin+( v(1)*x(1)+v(2)*x(2)+v(3)*x(3) )
irms=irms+x(1)**2
iav=iav+abs( x(1) )
e1rms=e1rms+e(1)**2
e1ave=e1ave+abs( e(1) )
vdave=vdave+vd
hsin6=hsin6+td*sin(6.0*ang)
hcos6=hcos6+td*cos(6.0*ang)
hsin12=hsin12+td*sin(12.0*ang)
hcos12=hcos12+td*cos(12.0*ang)

```

```

hsin18=hsin18+td*sin(18.0*ang)
hcos18=hcos18+td*cos(18.0*ang)
hsin24=hsin24+td*sin(24.0*ang)
hcos24=hcos24+td*cos(24.0*ang)
tx=t-tmxmn
txx=t*w*180.0/pi
write(1,2000) x(1)
write(2,3000) txx
write(3,2000) td
write(4,2000) v(1)
write(7,2000) vd
write(8,2000) x(1)+x(2)+x(3)
kount=0
if( t .lt. tmax ) go to 100
305 pd=pd/sum
pin=pin/sum
irms=irms/sum
irms=sqrt( irms )
iav=iav/sum
e1rms=e1rms/sum
e1rms=sqrt( e1rms )
e1ave=e1ave/sum
vdave=vdave/sum
hsin6=hsin6/sum
hcos6=hcos6/sum
h6=hsin6**2+hcos6**2
h6=sqrt( h6 )/6.0
hsin12=hsin12/sum
hcos12=hcos12/sum
h12=hsin12**2+hcos12**2
h12=sqrt( h12 )/12.0
hsin18=hsin18/sum
hcos18=hcos18/sum
h18=hsin18**2+hcos18**2
h18=sqrt( h18 )/18.0
hsin24=hsin24/sum
hcos24=hcos24/sum
h24=hsin24**2+hcos24**2
h24=sqrt( h24 )/24.0
600 tsav=(pd-pfw)/wm
write(6,*) ' tsav=',tsav
eff=(pd-pfw)/pin*100.0
if( eff .lt. 100.0 ) go to 710
eff=pin/(pd+pfw)*100.0
710 write(6,*) ' pin=',pin
write(6,*) ' eff=',eff
write(6,*) ' iav=',iav
write(6,*) ' irms=',irms
write(6,*) ' e1ave=',e1ave
write(6,*) ' vdave=',vdave

```

```
      write(6,*), h6=h6
      write(6,*), h12=h12
      write(6,*), h18=h18
      write(6,*), h24=h24
1000   format( 5(e12.4,5x) )
2000   format( e10.4 )
3000   format( f8.3 )
      call pclose(dummy)
      stop
      end
```







```
4      do 8 i=1,m
      j=i+100
      k=i+200
      l=i+300
8      x(i)=q(l)+ ( ( q(i)+2.00*q(k)+2.00*q(k)+f(i)*h )/6.00 )
      index=1
      return
      end
```

```

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cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c          subroutine f
c
c
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subroutine ff( index,t,f,x,xi,ang,del,v )
dimension f(6),v(6),x(6)
common rr,rd,r0,ra,r(6),pi,xla,xl0,e(6),vm,vdc,ivdon,imodon
rr=rd+ra
if( index .eq. 1 ) r(1)=rr
if( index .eq. 1 ) r(2)=rr
if( index .eq. 1 ) r(3)=rr
if( ang .ge. 0.0      .and. ang .lt. 1.0/3.0*pi ) goto 10
if( ang .ge. 1.0/3.0*pi .and. ang .lt. 2.0/3.0*pi ) goto 20
if( ang .ge. 2.0/3.0*pi .and. ang .lt. 3.0/3.0*pi ) goto 30
if( ang .ge. 3.0/3.0*pi .and. ang .lt. 4.0/3.0*pi ) goto 40
if( ang .ge. 4.0/3.0*pi .and. ang .lt. 5.0/3.0*pi ) goto 50
if( ang .ge. 5.0/3.0*pi .and. ang .lt. 6.0/3.0*pi ) goto 60

10   n1=1
n2=3
n3=2
if( icycle .eq. 1 ) iflag=0
itest=10
icycle=0
go to 100
20   n1=1
n2=2
n3=3
itest=20
go to 200
30   n1=2
n2=1
n3=3
itest=30
go to 100
40   n1=2
n2=3
n3=1
itest=40
go to 200
50   n1=3
n2=2
n3=1
itest=50
go to 100
60   n1=3

```

```

n2=1
n3=2
itest=60
icycle=1
go to 200
100  if( x(n2) .lt. -0.001 .and. index .eq. 1 ) iflag=itest
      if( x(n1) .lt. -0.001 .and. index .eq. 1 ) r(n1)=rr+1000.0*abs( x(n1) )
      if( x(n3) .gt. 0.001 .and. index .eq. 1 ) r(n3)=rr+1000.0*abs( x(n3) )
      if( iflag .eq. itest .and. index .eq. 1 ) r(n2)=rr+1000.0*abs( x(n2) )

      do 150 i=1,3
      if( r(i) .gt. 1000.0 ) r(i)=1000.0
150  continue

      xl=xla

      f(n1)=(-x(n1)*r(n1)+v(n1)-e(n1))/xl
      f(n2)=(-x(n2)*r(n2)+v(n2)-e(n2))/xl
      f(n3)=(-x(n3)*r(n3)+v(n3)-e(n3))/xl
      return

200  if( x(n2) .gt. 0.001 .and. index .eq. 1 ) iflag=itest
      if( x(n3) .gt. 0.001 .and. index .eq. 1 ) r(n3)=rr+1000.0*abs( x(n3) )
      if( x(n1) .lt. -0.001 .and. index .eq. 1 ) r(n1)=rr+1000.0*abs( x(n1) )
      if( iflag .eq. itest .and. index .eq. 1 ) r(n2)=rr+1000.0*abs( x(n2) )

      do 250 i=1,3
      if( r(i) .gt. 1000.0 ) r(i)=1000.0
250  continue

      xl=xla

      f(n1)=(-x(n1)*r(n1)+v(n1)-e(n1))/xl
      f(n2)=(-x(n2)*r(n2)+v(n2)-e(n2))/xl
      f(n3)=(-x(n3)*r(n3)+v(n3)-e(n3))/xl

      return
end

```









```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                                     c
c          subroutine vd             c
c                                     c
c                                     c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
subroutine fv( a,ang,v,vd,alphs,xlamda )
dimension a(6),v(6),alphs(2)
common rr,rd,r0,ra,r(6),pi,xla,xl0,e(6),vm,vdc,ivdon,imodon
beta=xlamda+alphs(1)
if( ivdon .eq. 1 .and. ifull .eq. 1 ) vd=vm*sin( beta*pi/3.0 )
if( ivdon .eq. 1 .and. ifull .eq. 0 ) vd=vm*sin( beta*pi/6.0 )
if( ivdon .eq. 0 ) vd=vdc
shift=30.0/180.0*pi
theta=shift+ang
call svxn( vx,theta,a )
van=vx
theta=shift+ang-2.0/3.0*pi
call svxn( vx,theta,a )
vbn=vx
theta=shift+ang+2.0/3.0*pi
call svxn( vx,theta,a )
ven=vx

v(1)=vd*van
v(2)=vd*vbn
v(3)=vd*ven
return
end

```

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c          subroutine fvap
c
c
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cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

subroutine fvap( wst,vap,alps )
common rr,rd,r0,ra,r(6),pi,xla,xl0,e(6),vm,vdc,ivdon,imodon
vaa=0.0
vab= vm*sin( wst+1.0/3.0*pi+alps )
vac=-vm*sin( wst+5.0/3.0*pi+alps )
if( wst .ge. 0.0/3.0*pi .and. wst .lt. 1.0/3.0*pi ) vap= vab
if( wst .ge. 1.0/3.0*pi .and. wst .lt. 2.0/3.0*pi ) vap= vac
if( wst .ge. 2.0/3.0*pi .and. wst .lt. 3.0/3.0*pi ) vap= vac
if( wst .ge. 3.0/3.0*pi .and. wst .lt. 4.0/3.0*pi ) vap= vaa
if( wst .ge. 4.0/3.0*pi .and. wst .lt. 5.0/3.0*pi ) vap= vaa
if( wst .ge. 5.0/3.0*pi .and. wst .lt. 6.0/3.0*pi ) vap= vab
return
end

```

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c          subroutine vxn
c
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
subroutine svxn( vx,th,a )
dimension a(6)
common rr,rd,r0,ra,r(6),pi,xla,xl0,e(6),vm,vdc,ivdon,imodon
vx=0.0
xa=0.0
xb=pi
xc=2.0*pi
a(6)=pi/2.0
th=th+2.0*pi
th=th-float( int(th/xc) )*xc
if( th .ge. xa+a(1) .and. th .lt. xa+a(2) ) vx=1.0
if( th .ge. xa+a(3) .and. th .lt. xa+a(4) ) vx=1.0
if( th .ge. xa+a(5) .and. th .lt. xa+a(6) ) vx=1.0
if( th .ge. xb-a(6) .and. th .lt. xb-a(5) ) vx=1.0
if( th .ge. xb-a(4) .and. th .lt. xb-a(3) ) vx=1.0
if( th .ge. xb-a(2) .and. th .lt. xb-a(1) ) vx=1.0
if( th .ge. xb+a(1) .and. th .lt. xb+a(2) ) vx=-1.0
if( th .ge. xb+a(3) .and. th .lt. xb+a(4) ) vx=-1.0
if( th .ge. xb+a(5) .and. th .lt. xb+a(6) ) vx=-1.0
if( th .ge. xc-a(6) .and. th .lt. xc-a(5) ) vx=-1.0
if( th .ge. xc-a(4) .and. th .lt. xc-a(3) ) vx=-1.0
if( th .ge. xc-a(2) .and. th .lt. xc-a(1) ) vx=-1.0
return
end

```